EM Symposium

IN HONOR OF RAJ MITTRA

Saturday, September 27, 2014

Daylong symposium and dinner

Recent Developments and Trends in Metamaterials

Douglas H. Werner, Director

Computational Electromagnetics and Antennas Research Lab

John L. and Genevieve H. McCain Chair Professor

Department of Electrical Engineering and Materials Research Institute

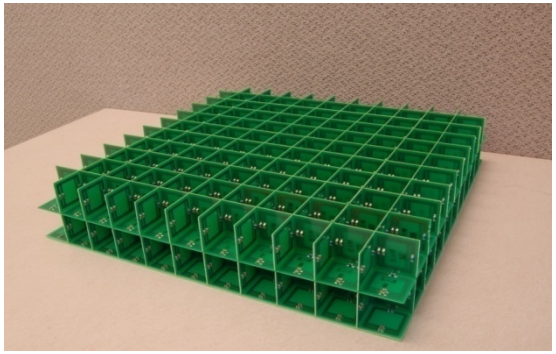
Pennsylvania State University

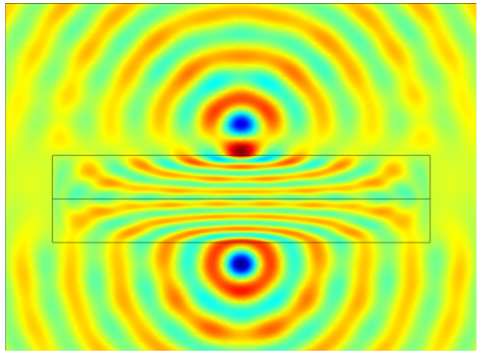
University Park, PA 16802

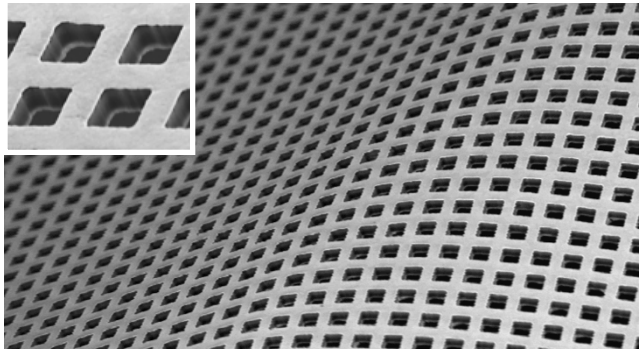
dhw@psu.edu

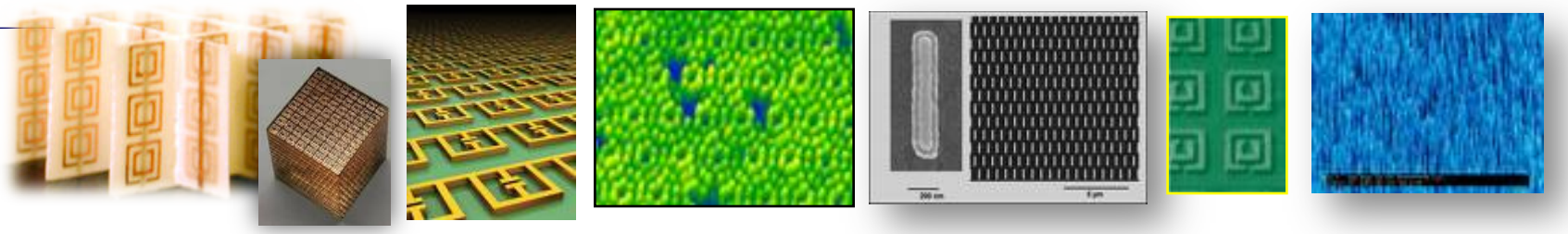
Overview

- Brief Introduction to Metasurfaces and Metamaterials
- Brief Introduction to Transformation Electromagnetics
- Examples of RF Metasurface/Metamaterial-Enabled Devices
- Examples of Optical Metasurface/Metamaterial-Enabled Devices
- Some Remarks on Future Trends





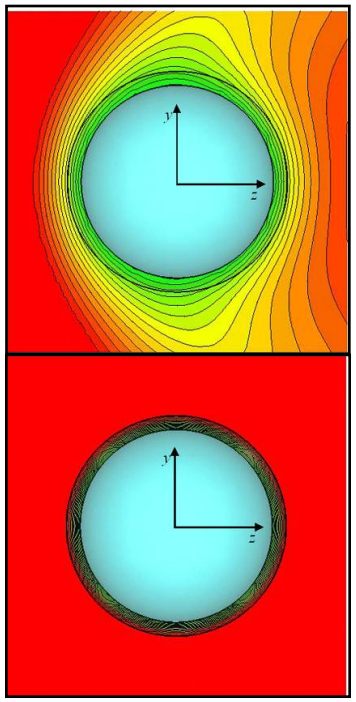




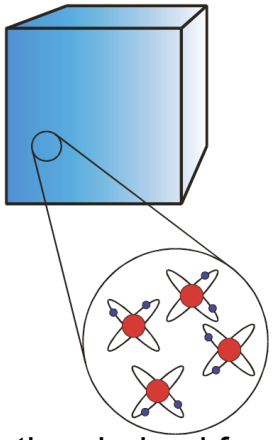
Electromagnetic Metamaterials

(Greek prefix "meta" – "beyond")

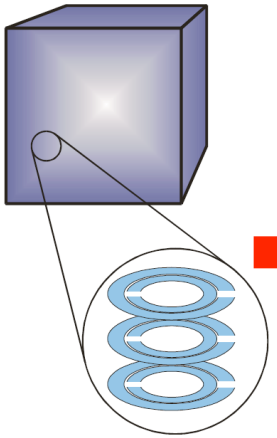
- Artificial materials that can be engineered to exhibit extraordinary electromagnetic properties that do not occur, or may not be readily found, in nature.
- Metamaterial-enabled devices have a wide range of applications in the RF, THz, IR, and visible spectrum.



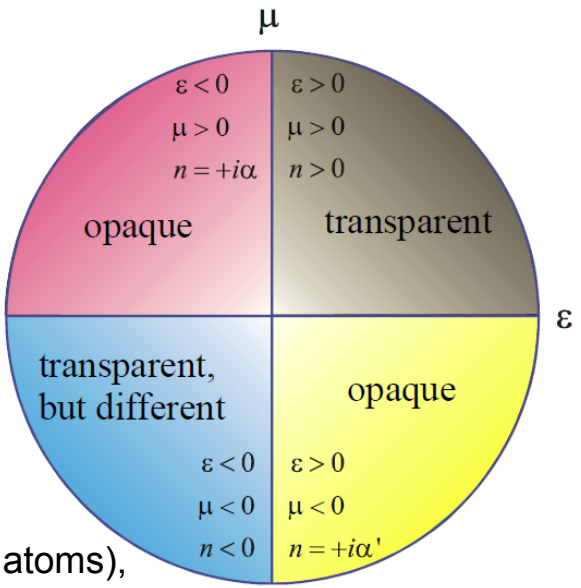
Conventional vs. Metamaterials



Properties derived from constituent *atoms*.



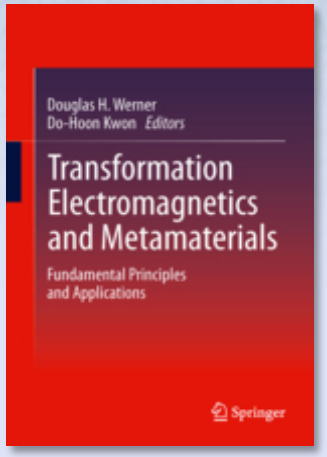
Properties derived from constituent *units* (artificial atoms), which can be engineered.

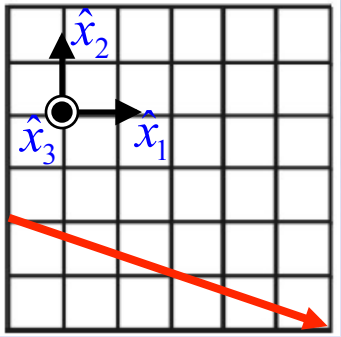


Transformation Electromagnetics/Optics

Original (x_1,x_2,x_3) system

Transformed (q_1,q_2,q_3) system

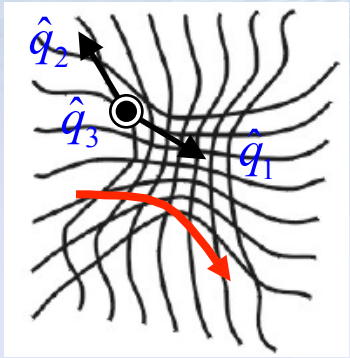




$$q_i = q_i(x_1, x_2, x_3);\ i = 1,2,3.$$

Jacobian Matrix **A**

$$\mathbf{A} = A_{ij} = \frac{\partial q_i}{\partial x_j};\ i, j = 1,2,3.$$



Maxwell's equations (source free)

$$\nabla \times \mathbf{E} = -j\omega\boldsymbol{\mu}\mathbf{H} \qquad \nabla_q \times \mathbf{E}_q = -j\omega\boldsymbol{\mu}_q\mathbf{H}_q$$

$$\nabla \times \mathbf{H} = j\omega\boldsymbol{\varepsilon}\mathbf{E} \qquad \nabla_q \times \mathbf{H}_q = j\omega\boldsymbol{\varepsilon}_q\mathbf{E}_q$$

Quantity	Fields	Materials
Relationship	$\mathbf{H}_q = \left(\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{H}$ $\mathbf{E}_q = \left(\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{E}$	$\boldsymbol{\varepsilon}_q = \frac{\mathbf{A}\boldsymbol{\varepsilon}\mathbf{A}^{\mathrm{T}}}{\det(\mathbf{A})}$ $\quad \boldsymbol{\mu}_q = \frac{\mathbf{A}\boldsymbol{\mu}\mathbf{A}^{\mathrm{T}}}{\det(\mathbf{A})}$ Interpret as new material in (x_1,x_2,x_3)

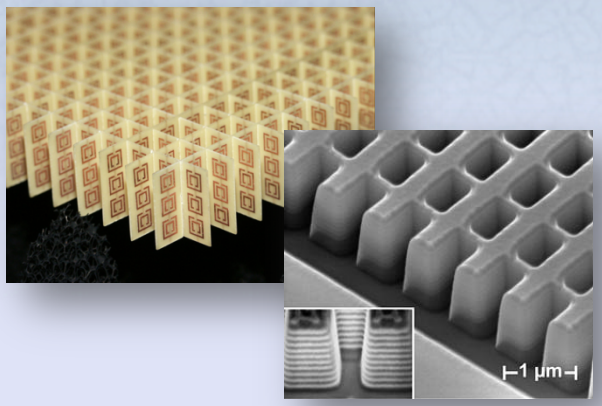
J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling Electromagnetic Fields," *Science*, Vol. 312, pp. 1780-1782, 2006.

D. H. Werner, and D.-H. Kwon, *Transformation Electromagnetics and Metamaterials: Fundamental Principles and*

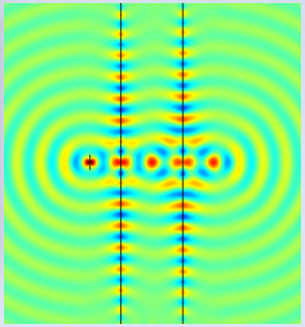
PENNSTATE

Metamaterials and Transformation Optics

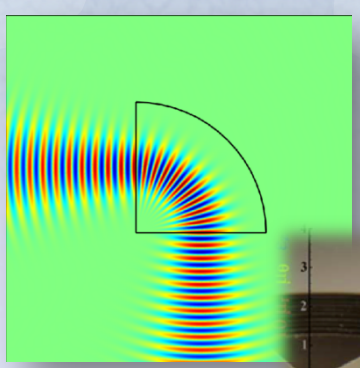
Negative Index Materials



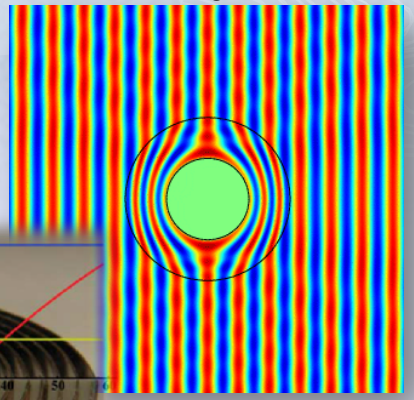
Perfect Lens

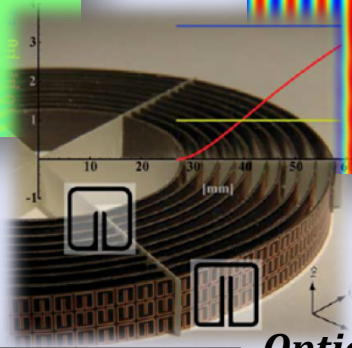


Beam Bender

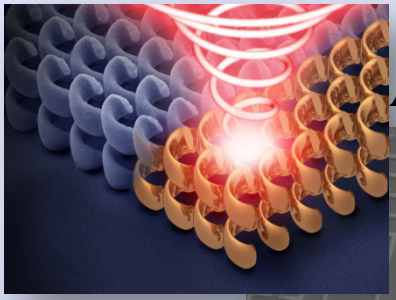


Invisibility Cloaks

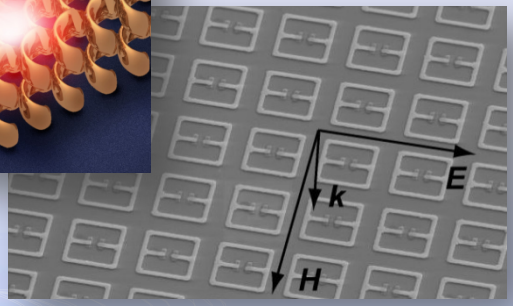




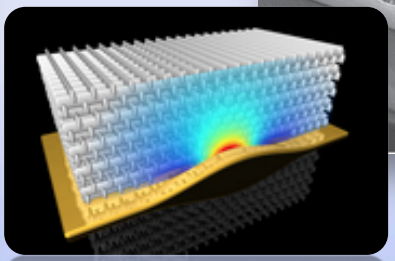
Chiral Metamaterial

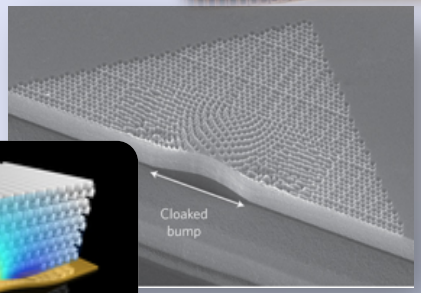


Active Metamaterial

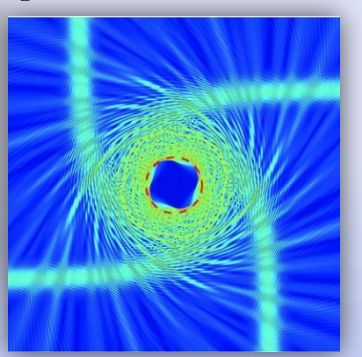


Carpet Cloak





Optical Black Hole

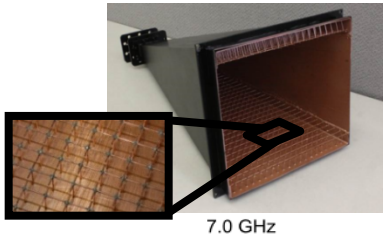


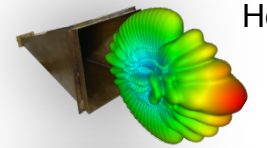
The metamaterial technology and transformation optics approach enables unprecedented design flexibility and novel device applications.

Groundbreaking Meta-Antennas

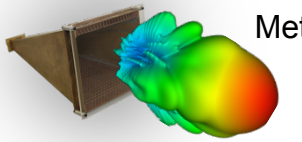
Octave Bandwidth Negligible Loss Metahorn Antenna

A wire-grid metamaterial gives low E-plane sidelobes from 3.4 GHz to 7.0 GHz.

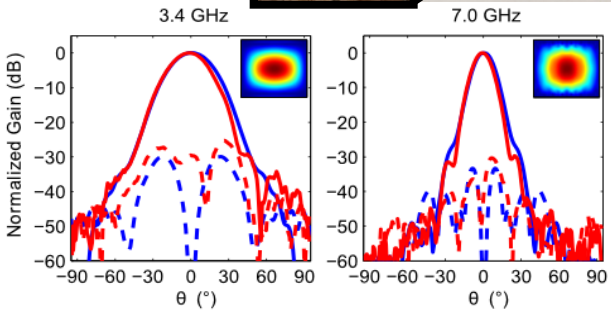




Conventional Horn



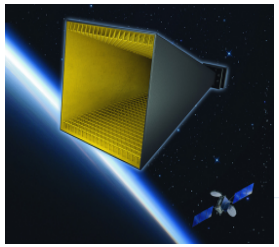
Metahorn



nature materials
ARTICLES
PUBLISHED ONLINE: XX MONTH XXXX | DOI:10.1038/NMAT2950

An octave-bandwidth negligible-loss radiofrequency metamaterial

Erik Lier[1], Douglas H. Werner[2], Clinton P. Scarborough[3], Qi Wu[3] and Jeremy A. Bossard[4]*



Press Coverage:

The New York Times

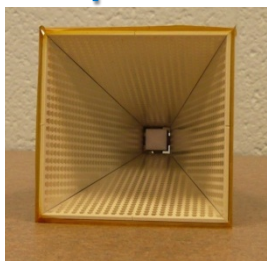
ScienceDaily — Your source for the latest research news

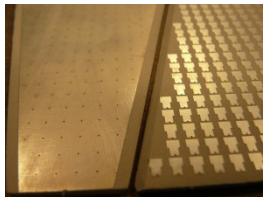
MicroWaves&RF — TRUSTED ENGINEERING RESOURCE FOR 50 YEARS

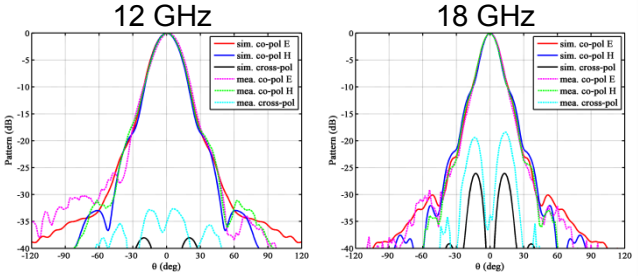
PHYSORG.COM — SCIENCE : PHYSICS : TECH : NANO : NEWS

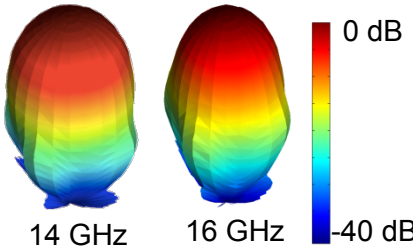
ThomasNet NEWS

Broadband Square Metahorn with Polarization-Independent Radiation Patterns





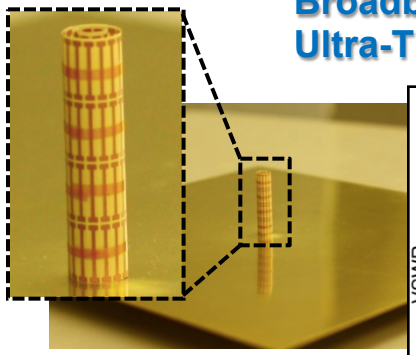


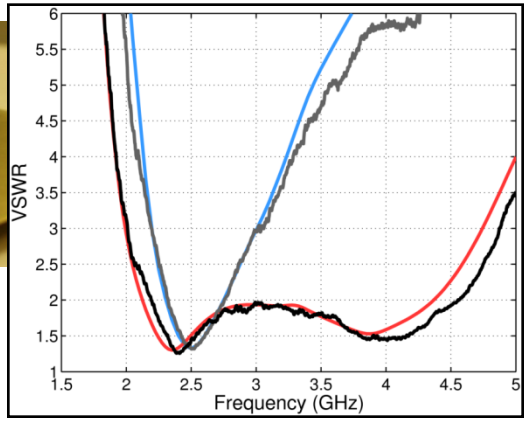


Lightweight*, low cost alternative to machined, heavy corrugated horns

* Critical for Space Applications

Broadband Monopole Enabled by Ultra-Thin Metamaterial Coating

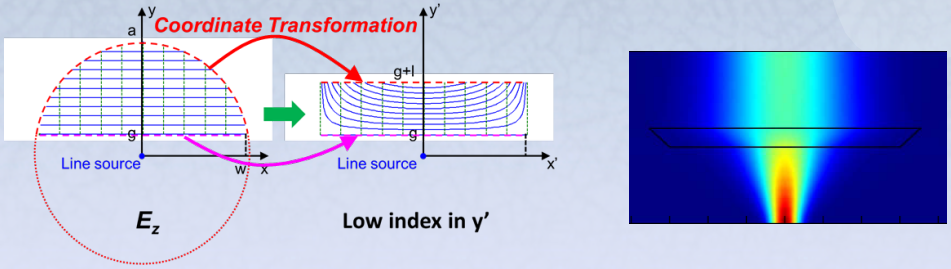


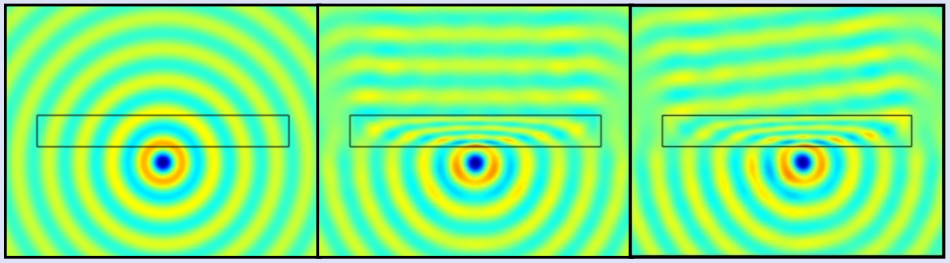


Measurements confirmed that the metamaterial increased the bandwidth to over an octave while preserving the radiation pattern of a simple monopole.

Transformation Optics Lenses

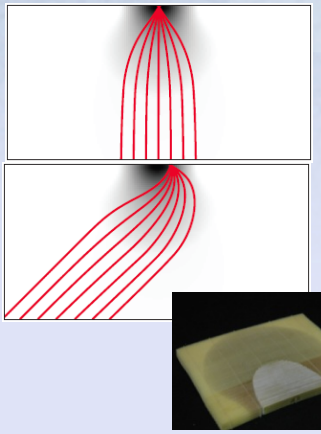
Transformation Optics (TO) Collimating Lenses

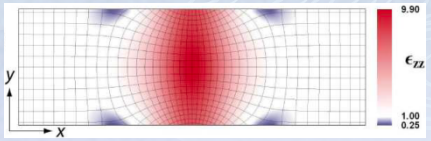


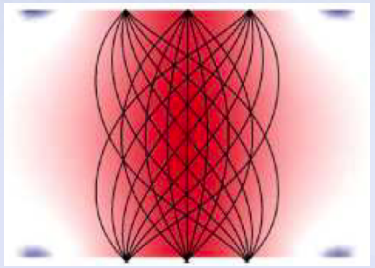


D.-H. Kwon and D. H. Werner, *New J. Phys.* 10, 115023 (2008).
D.-H. Kwon and D. H. Werner, *IEEE Antenn. Wire. Propag. Lett.* 8, 1115 (2009).
D.-H. Kwon and D. H. Werner, *Opt. Express* 17, 7807 (2009).

TO Luneburg and Maxwell Fish-eye Lenses

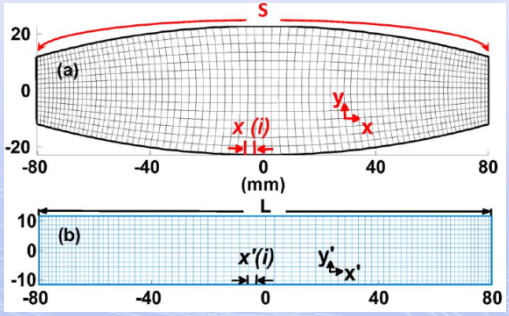


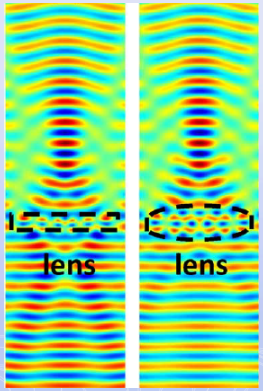




N. Kundtz and D. R. Smith, *Nat. Mater.* 9, 129 (2010).
D. R. Smith, Y. Urzhumov, N. B. Kundtz, and N. I. Landy, *Opt. Express* 18, 21238 (2010).

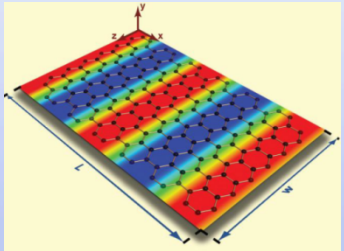
TO All-dielectric Flat Lenses

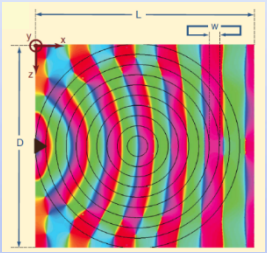


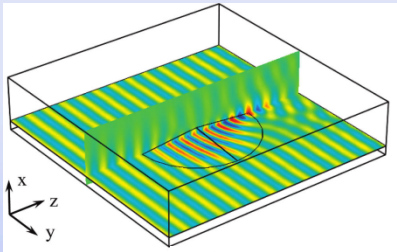


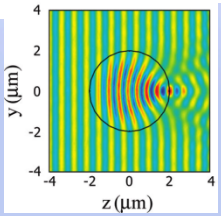
W. Tang, C. Argyropoulos, E. Kallos, W. Song, and Y. Hao, *IEEE Trans. on Antennas and Propagation* 58, 3795 (2010).

2D Luneburg Lenses with Graphene and Surface Plasmons



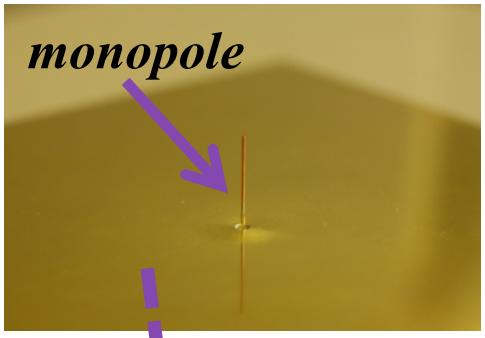


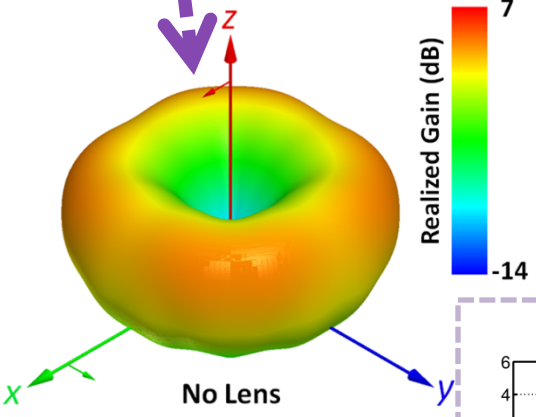




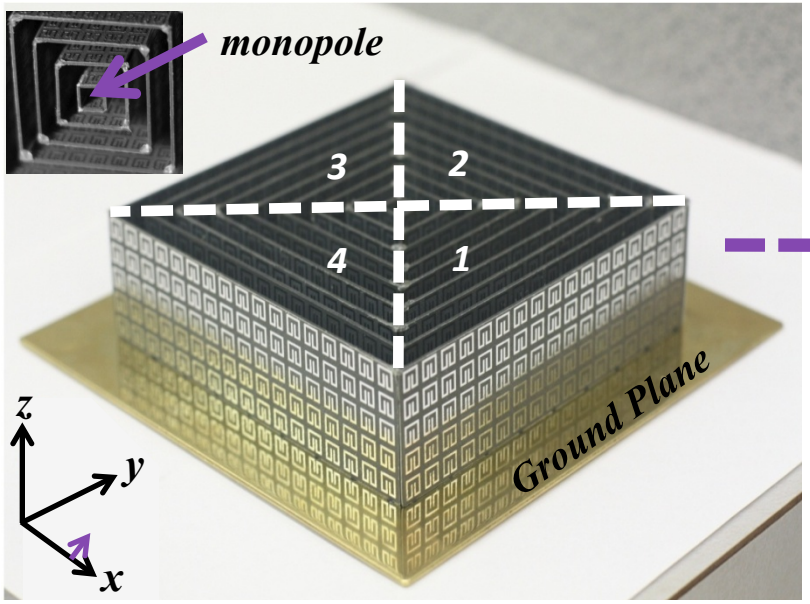
Vakil and N. Engheta, *Science* 332, 1291 (2011).
Y. Liu, T. Zentgraf, G. Bartal, and X. Zhang, *Nano Lett.* 10, 1991 (2010).

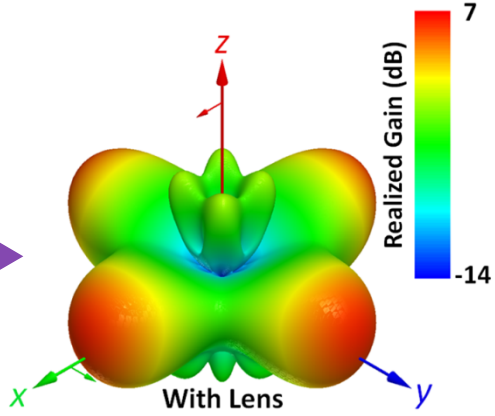
Metamaterial Lenses for Multi-Beam Radiation - 3D Radiation Pattern Comparison





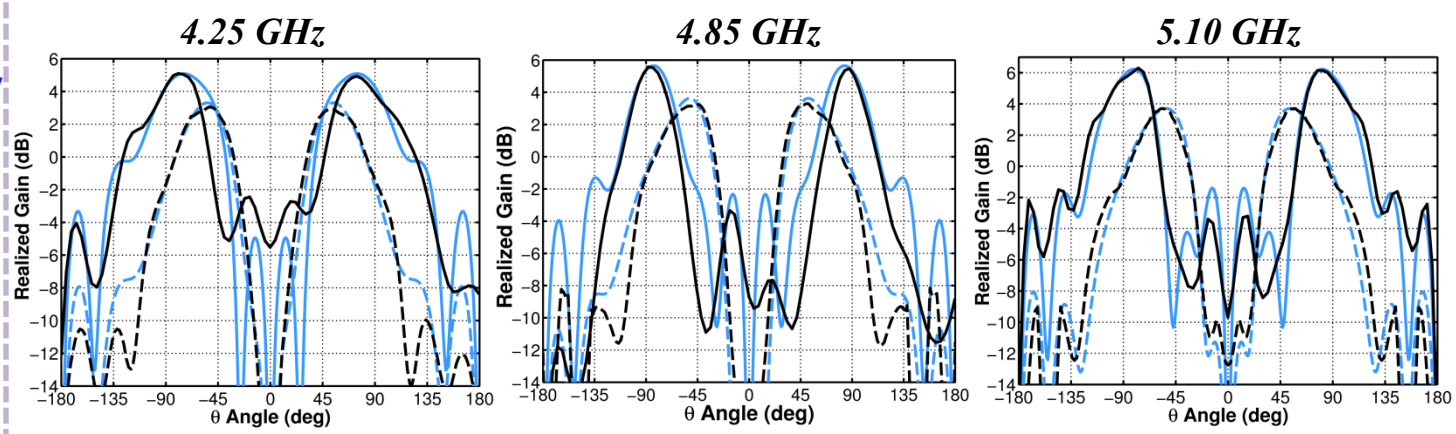
Radiation Pattern





Radiation Pattern

A redistribution of the radiated energy in desired directions!

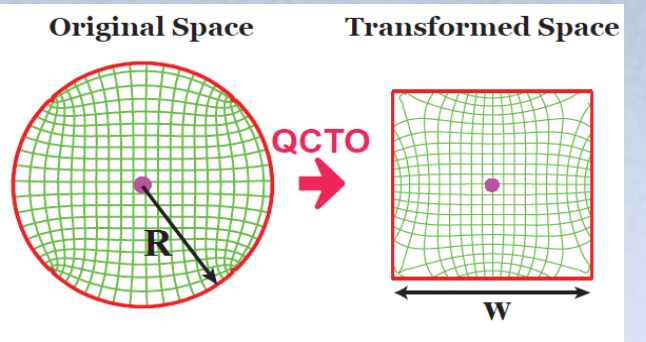


Simulation without the lens (dashed blue lines), simulation with the lens (solid blue lines), measurement without the lens (dashed black lines), measurement with the lens (solid black lines).

The simulated and measured E-plane realized gain patterns with and without the lens confirm the wave bending effect in the elevation plane.

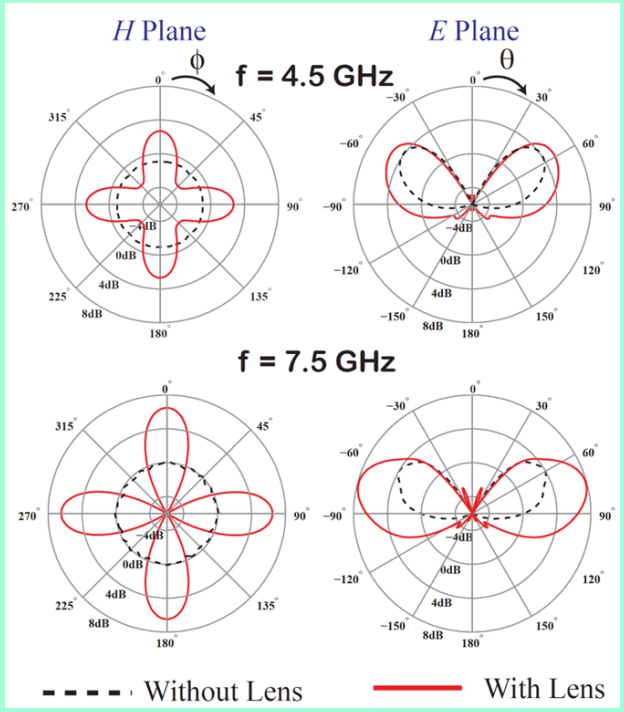
Z. H. Jiang, M. D. Gregory, and D. H. Werner, "Experimental Demonstration of a Broadband Transformation Optics Lens for Highly Directive Multibeam Emission," *Phys. Rev. B*, vol. 84, pp. 165111/1-6, October 2011.

TO Lens Antennas for Broadband Directive Radiation

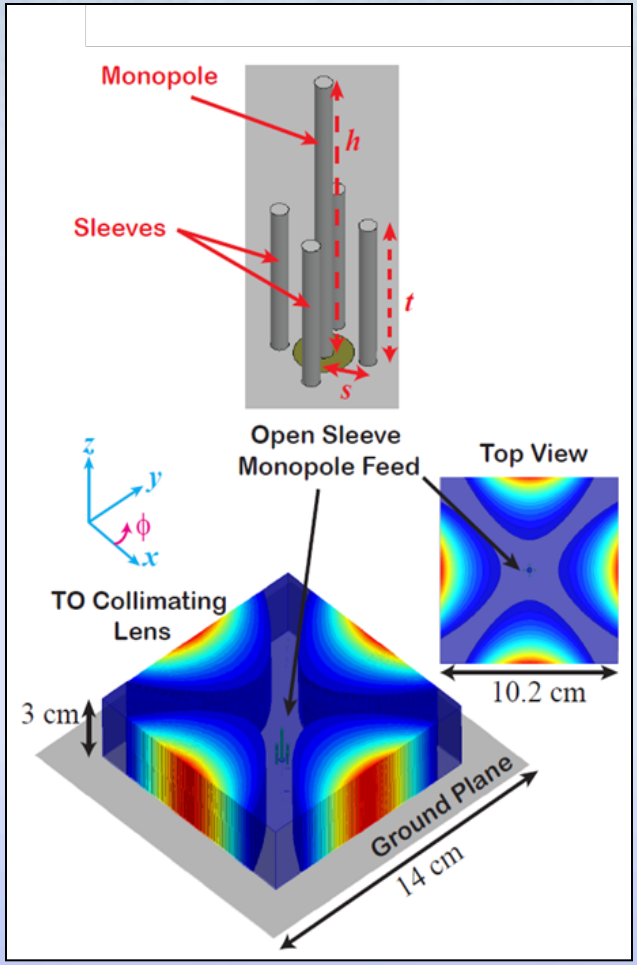


Coordinate Transformation

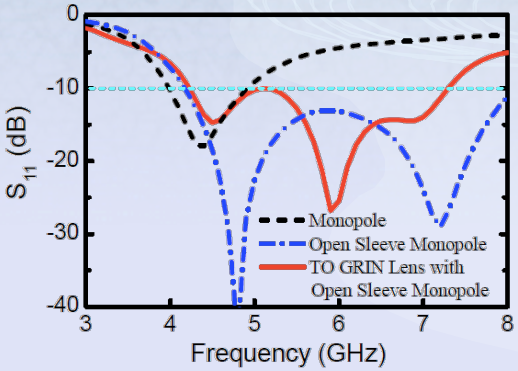
Radiation Patterns

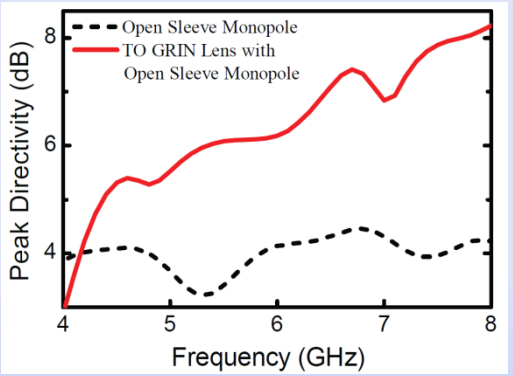


Broadband Multi-beam Antenna with Simple Feed Structures



Broad Impedance and Radiation Bandwidth

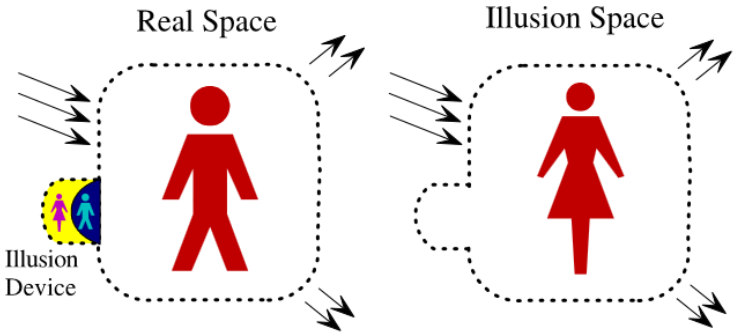




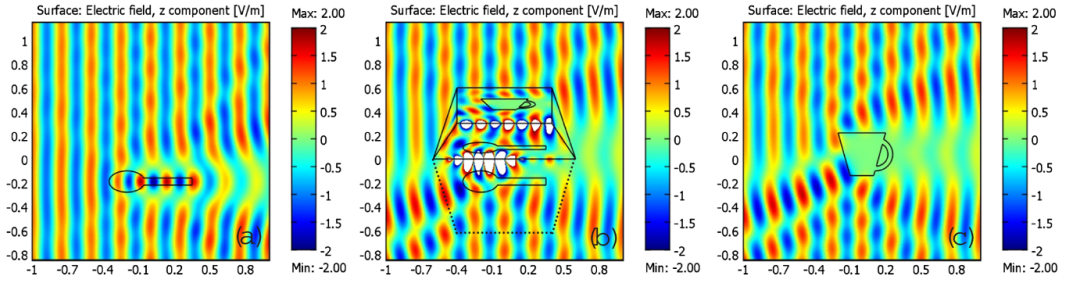
Q. Wu, Z. H. Jiang, O. Quevedo-Teruel, J. P. Turpin, W. Tang, Y. Hao, and D. H. Werner, "Transformation Optics Inspired Multibeam Lens Ante for Broadband Directive Radiation," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 12, pp. 5910-5922, Dec. 2013.

Electromagnetic Illusion

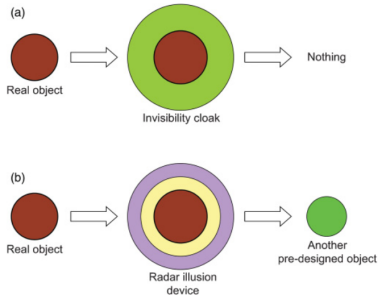
Transformation optics was used to generate a general illusion such that an arbitrary object appears to be like some other object.

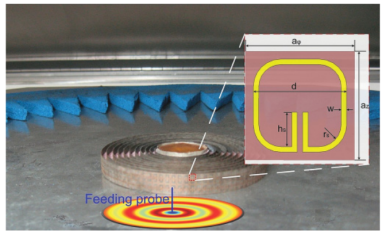


* Lai *et al.*, *PRL*, **102** (2009).



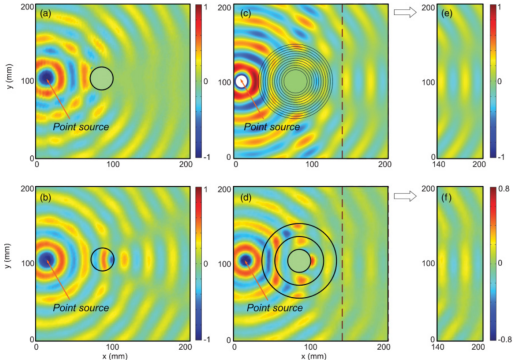
The scattering of a dielectric spoon looks like a metallic cup



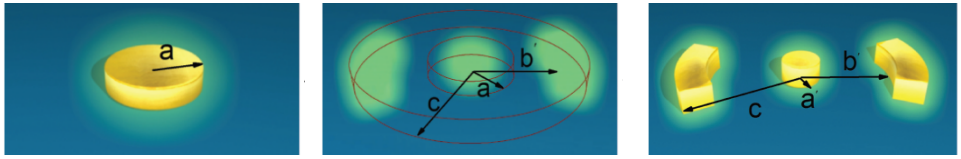


* Jiang *et al.*, *PRE*, **83**, 2011

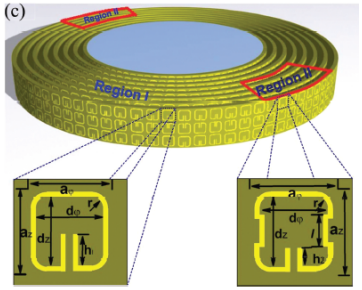
Bulk Multilayer Metamaterial Coating

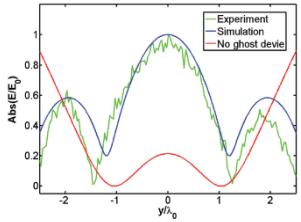


A PEC cylinder looks like a dielectric cylinder



Creating multiple "ghost" wing illusions using multilayer TO-based metamaterial coatings.

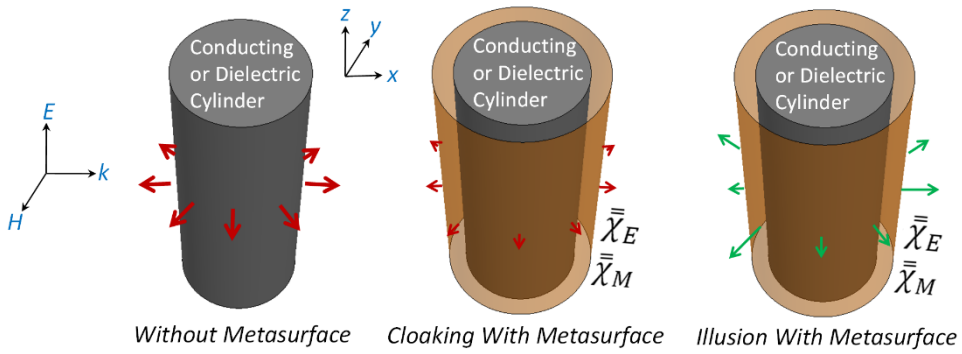




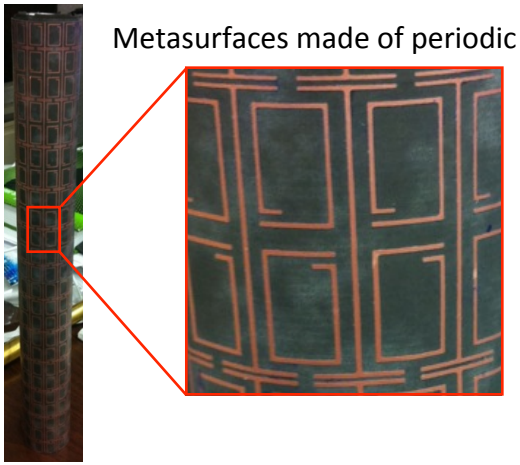
* Jiang *et al.*, *AFM*, **23**, 2013

Electromagnetic Illusion Created by Metasurfaces

Using a single layer metasurface to achieve illusion.

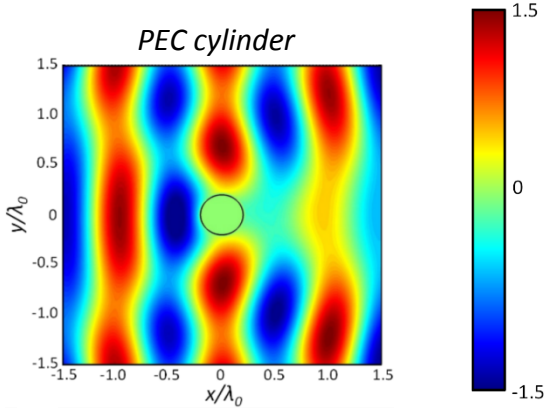


Without Metasurface *Cloaking With Metasurface* *Illusion With Metasurface*

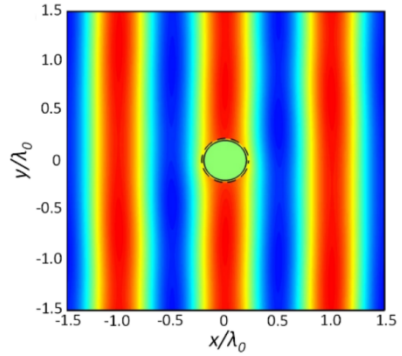


Metasurfaces made of periodic metallic patterns

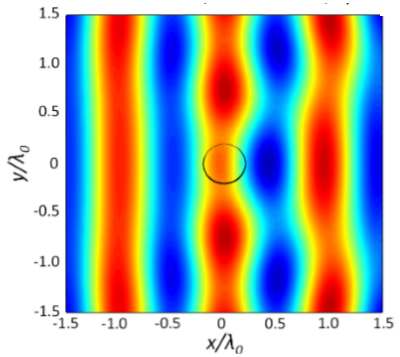
PEC cylinder



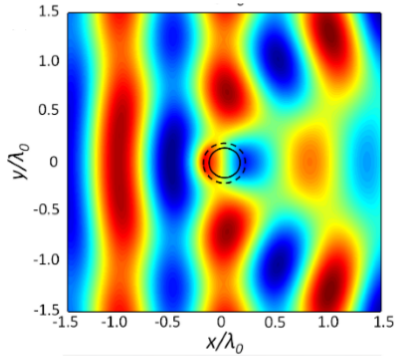
PEC cylinder with metasurface coating to mimic free space



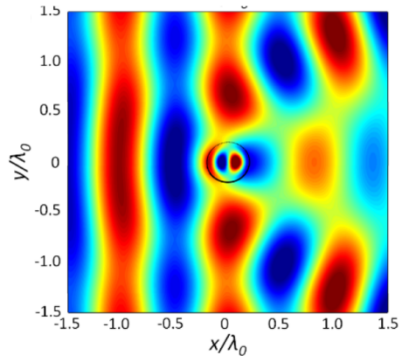
Dielectric cylinder 1 (ε_r = 2)



Dielectric cylinder 2 (ε_r = 20)

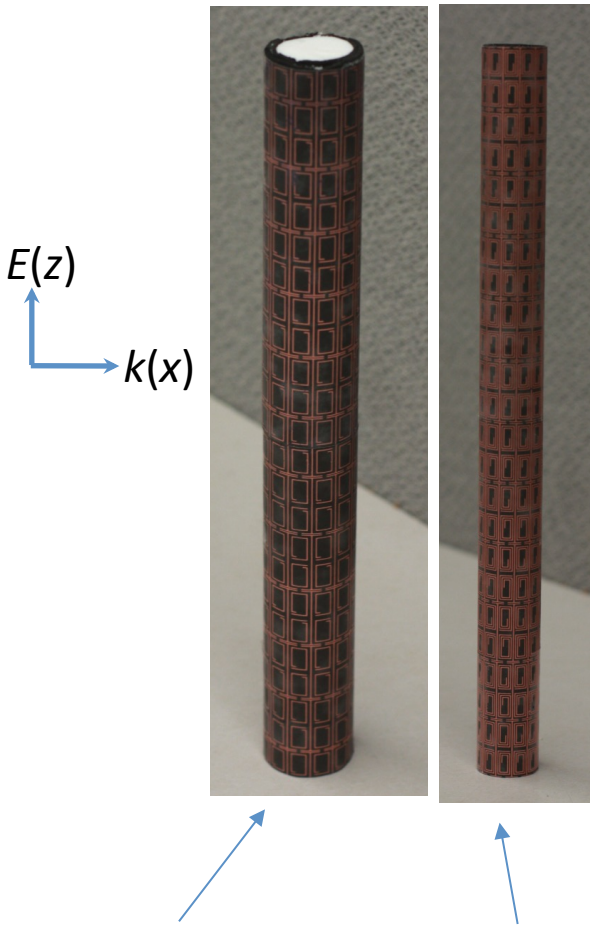


Dielectric cylinder 1 with metasurface coating to mimic dielectric cylinder 2



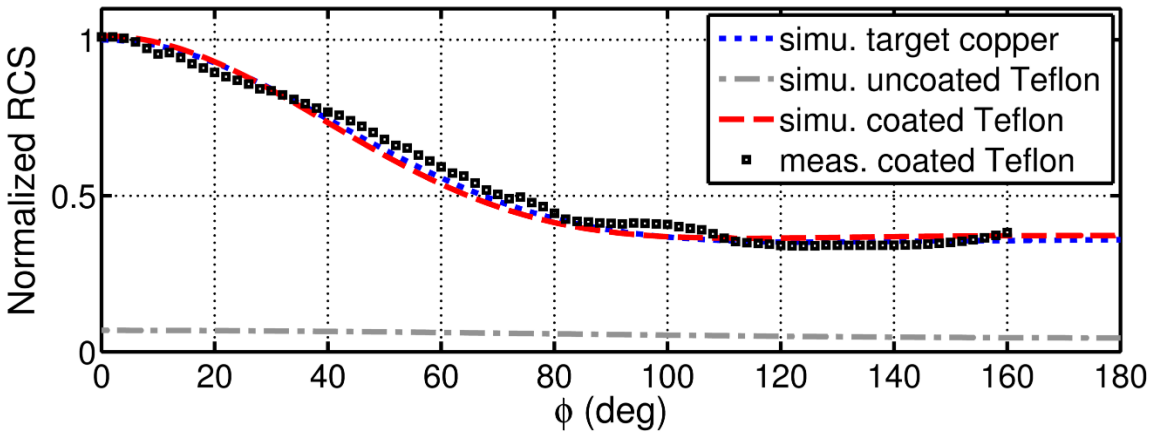
Metasurface Illusion

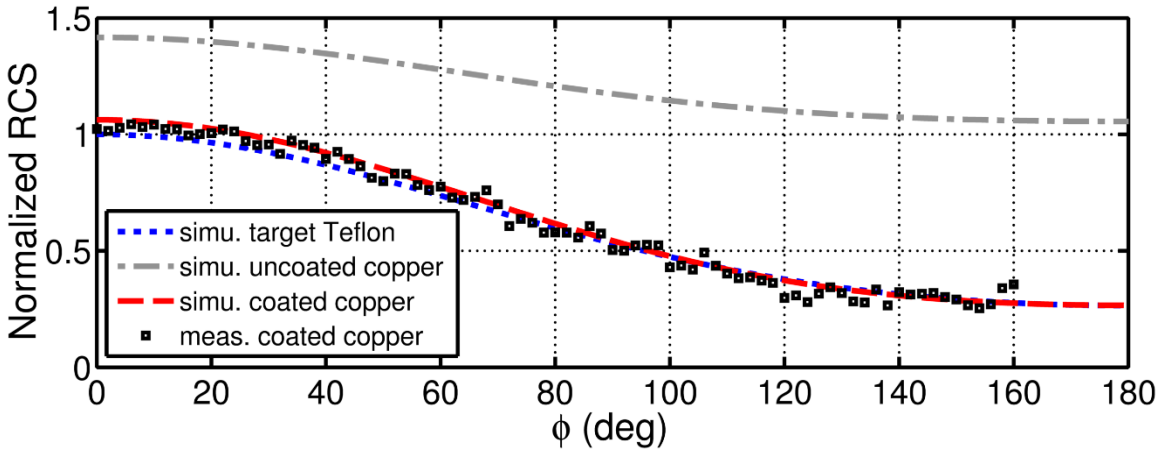
- *Finite cylinder: 2.34λ_0 long at 2.5 GHz, 12 unit cells in the z-direction.*
- *The scattering patterns were measured in the x-y plane using two horn antennas in an anechoic chamber.*



Metasurface coated Teflon cylinder

Metasurface coated copper cylinder





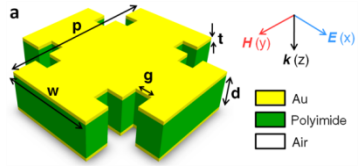
Very good agreement was achieved, demonstrating the illusion effect using a single metasurface coating with super scattering.

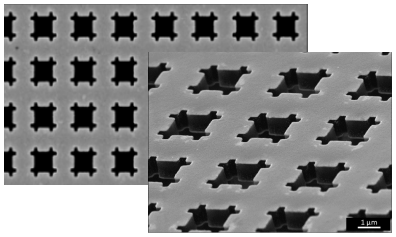
Accepted for publication in *Advanced Functional Materials*

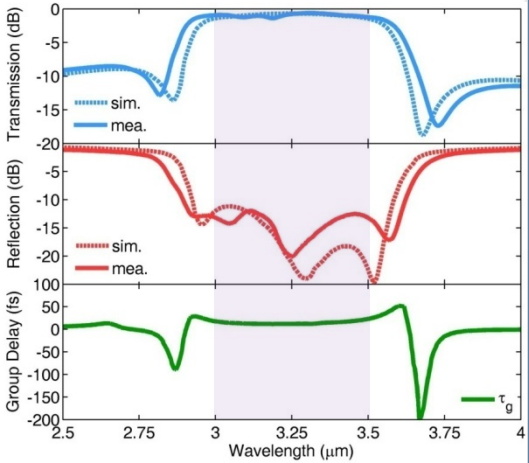
Optical Metamaterial Filters and Mirrors

Broadband Dispersion Engineered Photonic Metamaterial Filter

Transmission band: 3 ~ 3.5 μm
Mean in-band insertion loss: < 1dB
Mean out-of-band transmission: ~ -10.1dB
In-band group delay variation: ~ 12fs

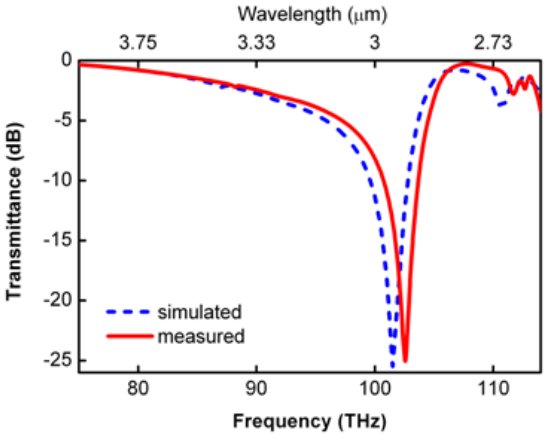






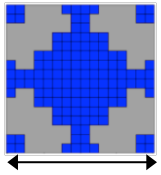
Z. Jiang, et al., Scientific Reports, 3, 1571 (2013).

Angle-tolerant Mid-IR All-Dielectric FSS Filter



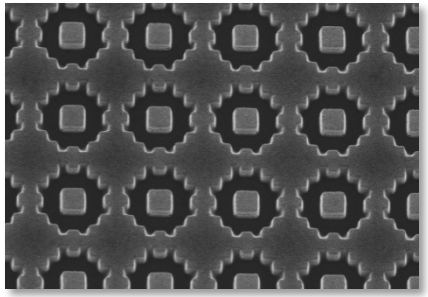
S. Yun, et al., Appl. Phys. Lett., 96, 223101 (2010).

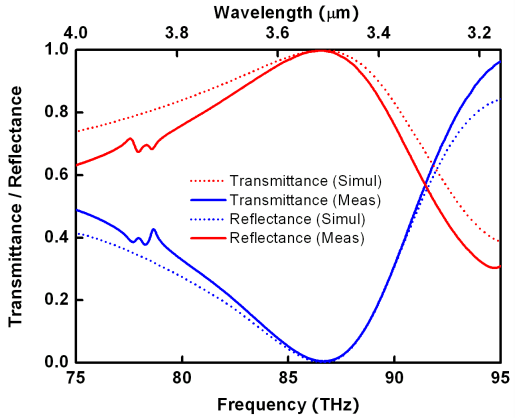
All-Dielectric ZIM Perfect Mirror



2.05 μm

468nm patterned *a*-Si on 0.5mm fused silica

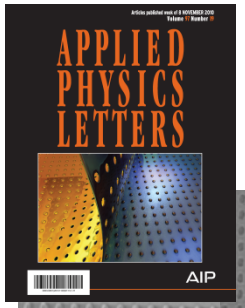


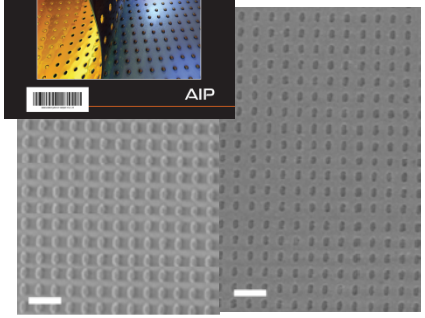


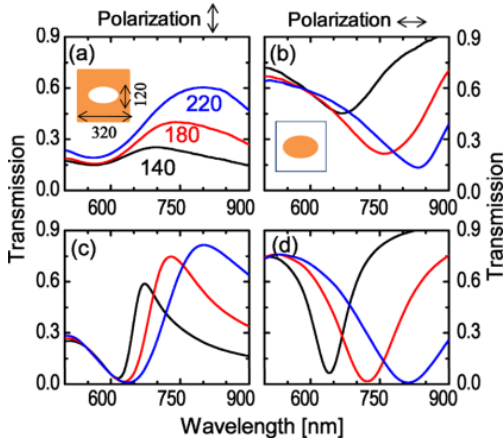
Solid: Measurements
Dots: Simulations

S. Yun, et al., Appl. Phys. Lett., 102, 171114 (2013).

Optical Complementary Metallic Membranes





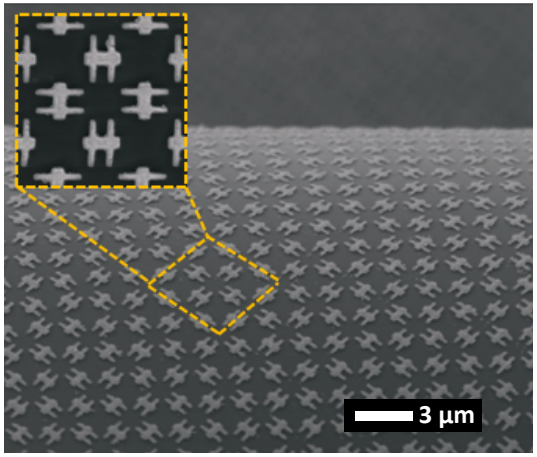


Q. Hao, et al., Appl. Phys. Lett., 97, 193101 (2010).

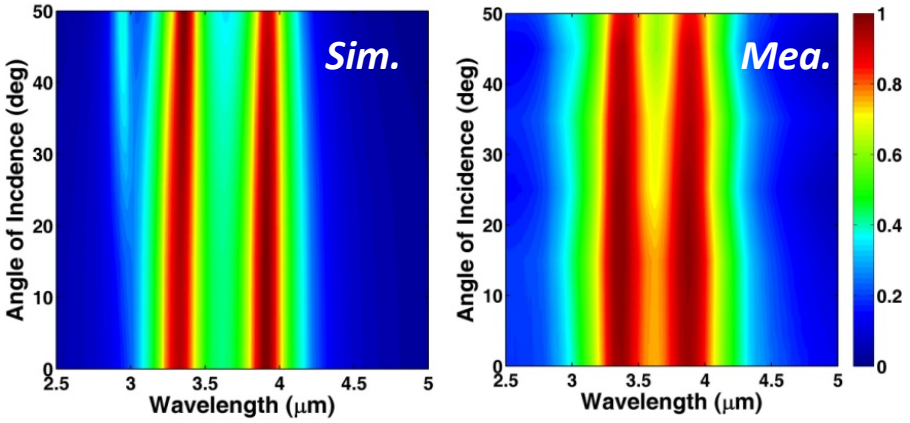
Exploiting Loss in Metamaterial Absorbers

Dual-Band Absorber with Wide FOV

By exploiting the loss in the metamaterial structure, we can optimize absorbing structures.

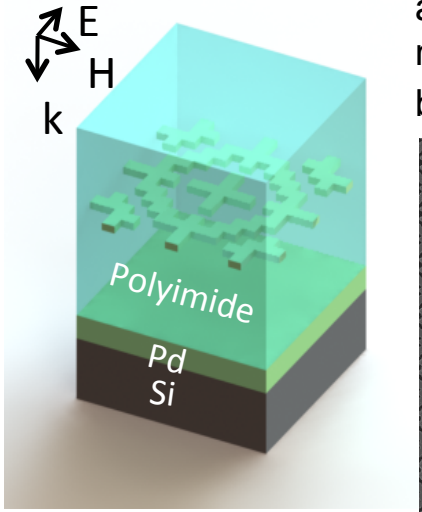


This Au-polyimide structure was optimized to have dual absorption bands with a θ≤50° Field-of-View.

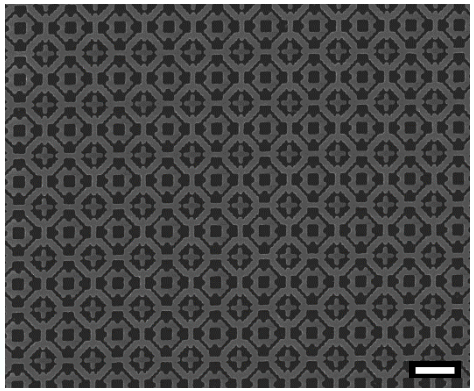


*Z. Jiang, S. Yun, F. Toor, D. H. Werner & T. S. Mayer, *ACS Nano* **5**, pp. 4641-4647 (2011).

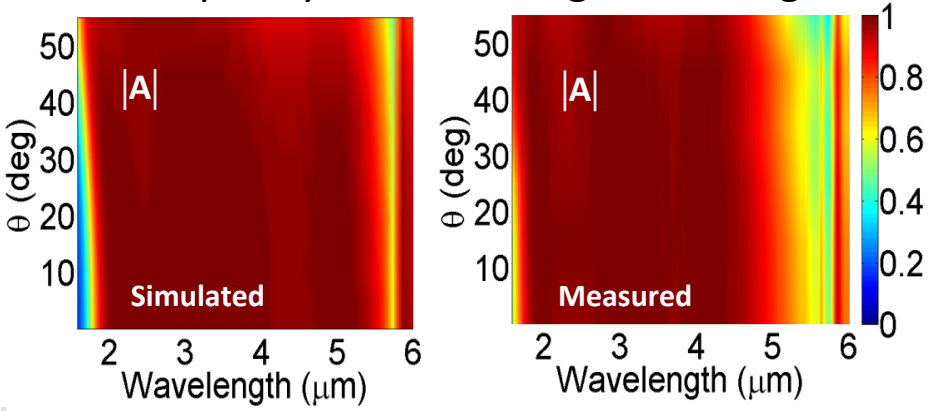
Broadband Super-Octave Mid-IR Absorber



This Au-polyimide metamaterial absorber was optimized to have more than an octave of bandwidth in the Mid-IR.



Absorptivity vs. Wavelength and Angle



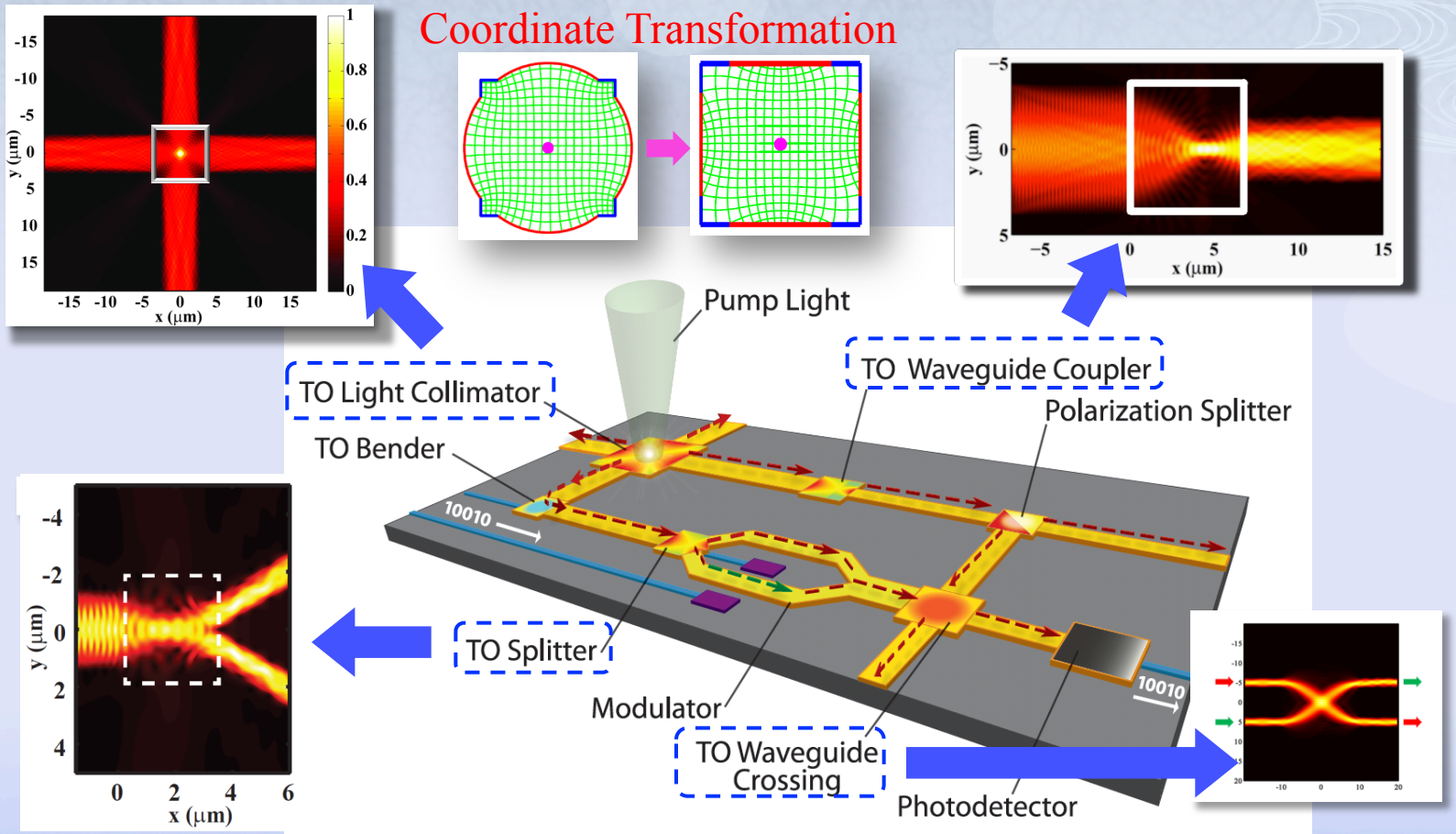
* J. A. Bossard, *et al.*, *ACS Nano*, **8**(2), pp. 1517-1524 (2014).

PENNSTATE

Future Trends

- Rapid growth in the application space for metasurfaces, especially in the area of novel optical coatings technology
- Reconfigurable and tunable metamaterials
- Fabrication of 3D optical metamaterials using bottom-up and/or hybrid assembly techniques
- Development of design approaches that stress practical material properties for the realization of transformation optics devices
- Efficient analysis/design techniques for 3D transformation optics devices
- Consider systems of transformation optics components rather than focusing on individual devices

Integrated Photonic Systems Based on Transformation Optics Devices



Transformation optics devices that perform diverse, simple functions can be integrated together on a chip to build complex photonic systems for optical communications, imaging, computing, and sensing.

Q. Wu, J. P. Turpin, and D. H. Werner, "Integrated photonic systems based on transformation optics enabled gradient index devices." *Light: Science & Applications*, 1:e38 (2012).

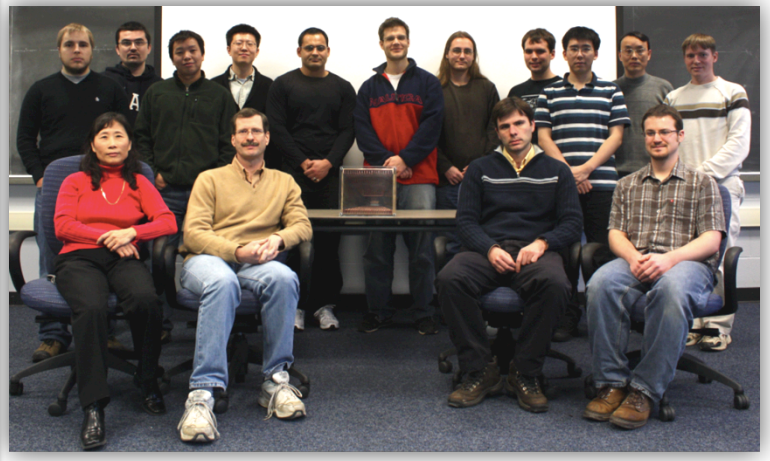
Backup Slides

Prof. Werner's CEARL Group

Prof. Douglas H. Werner, Director	
Prof. Pingjuan L. Werner, Associate Director	
Dr. Micah Gregory	Research Associate
Dr. Xiande Wang	Research Associate
Dr. Jeremy Bossard	Post doc
Dr. Sawyer Campbell	Post doc
Dr. Zhihao Jiang	Post doc
Dr. Lei Kang	Post doc
Dr. Anastasios Panaretos	Post doc
Jason Ashbach	Ph.D. Student
Donovan Brocker	Ph.D. Student
Cooper Cicero	Ph.D. Student
Bingqian Lu	Ph.D. Student
Idellyse Martinez	Ph.D. Student
Zachery Morgan	Ph.D. Student
Jogender Nagar	Ph.D. Student
Yifeng Qin	Ph.D. Student
Clinton Scarborough	Ph.D. Student
Peter Sieber	Ph.D. Student
Jeremy Turpin	Ph.D. Student
Kenneth Morgan	M.S. Student

At least 50 **Awards and Recognitions** have been received by the students and post-docs in CEARL since 1998 which include several prestigious **Best Paper Awards** given by international journals/societies, **Feature Articles** (selected for cover art) in highly rated international journals, as well as numerous Student **Research Competition Awards** given by international professional societies such as the IEEE, the University, the College and the Department.

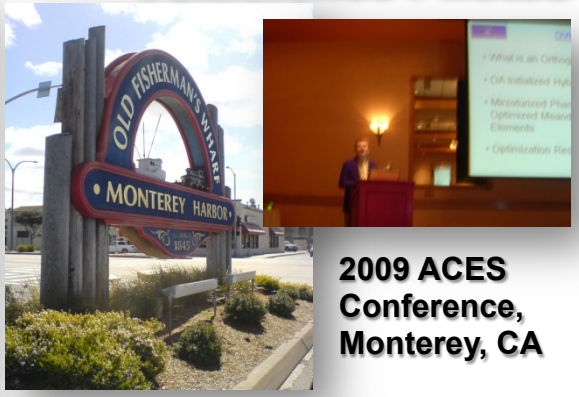
CEARL Group



- We have at least 600 published journal articles and conference proceedings:
  - ***IEEE Trans. on Nanotechnology***
  - ***Nature Materials***
  - ***Optics Express***
  - ***Physics Review B***
  - ***JOSA B***
  - ***ACS Nano***
  - ***Journal of Applied Physics***
  - ***Applied Physics Letters***
  - ***New Journal of Physics***
  - ***IEEE Antennas and Propag. Mag.***
  - ***IEEE Trans. on Antennas and Propag.***
  - ***IEEE Antennas and Wireless Propagation Letters …***

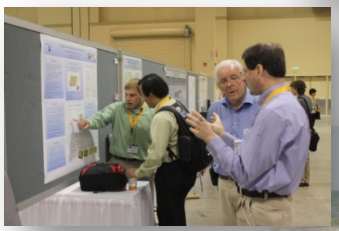
Conference Photos

2010 IEEE APS Conference, Toronto, Canada

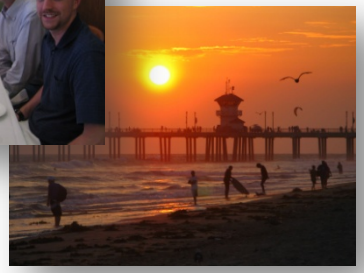


2009 ACES Conference, Monterey, CA

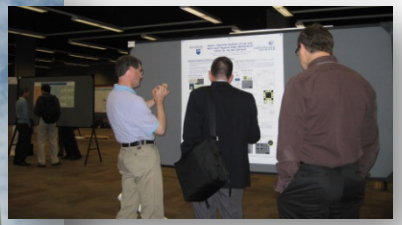
2008 Metamaterial Conference, Barcelona, Spain



2009 IEEE APS Conference, Charleston, SC



2008 IEEE APS Conference, San Diego, CA



2008 URSI Conference, Chicago, IL

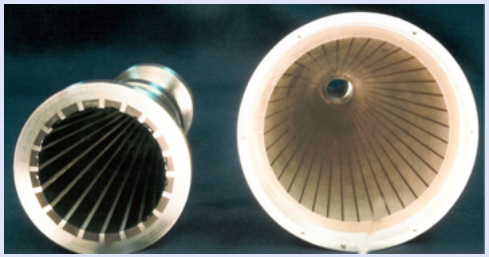
Hybrid-Mode Horn Antennas

Corrugated Horns

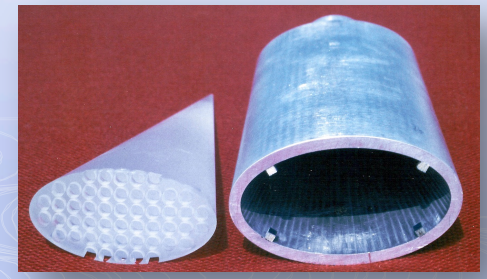
- Hybrid-mode horns for satellite antennas
  - Axially symmetric patterns
  - Low cross-polarization, dual polarized antennas
  - Broadband operation
  - Ideal feeds for reflectors

- Hybrid-mode horn implementations
  - Corrugated horns, strip loaded horns
  - Dielectric loaded horns
- Metamaterials with dielectric constant less than unity
  - Larger bandwidth than corrugated horns
  - Lower weight and loss than dielectric-loaded horns

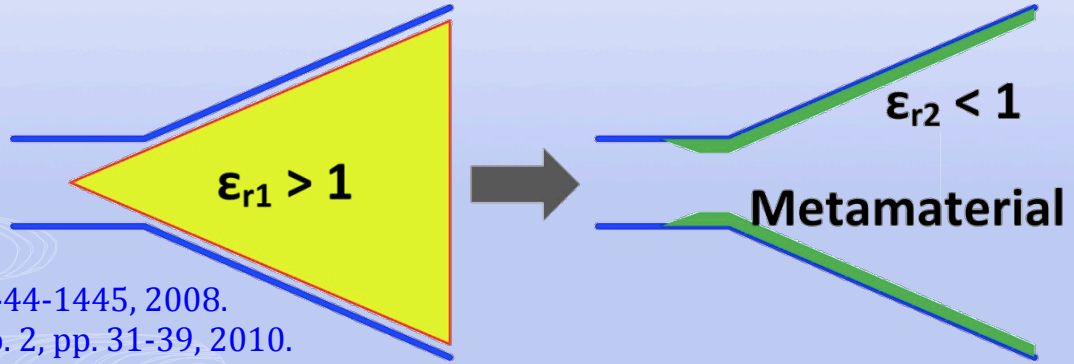
Strip Loaded Horns



Dielectric Loaded Horns

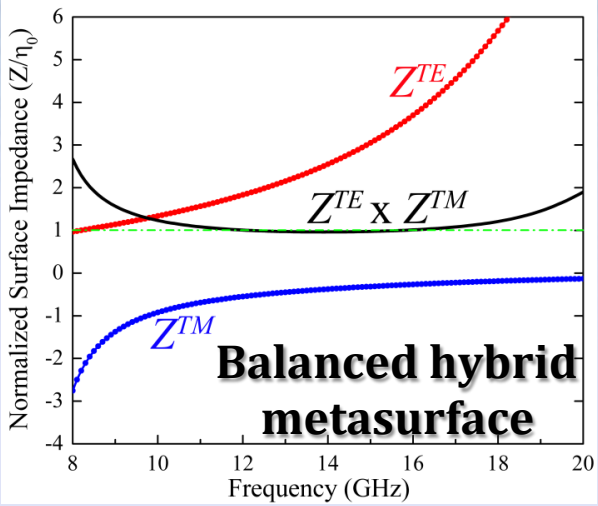


Metamaterial-based hybrid-mode soft horn

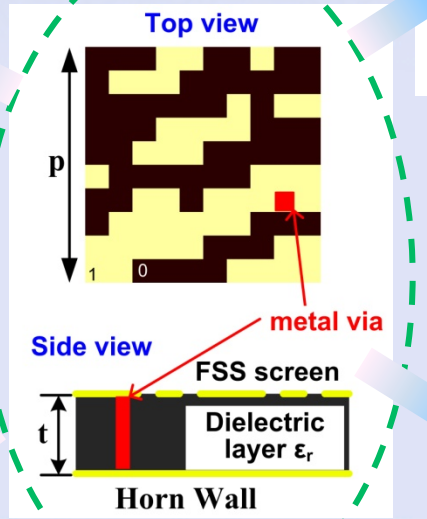


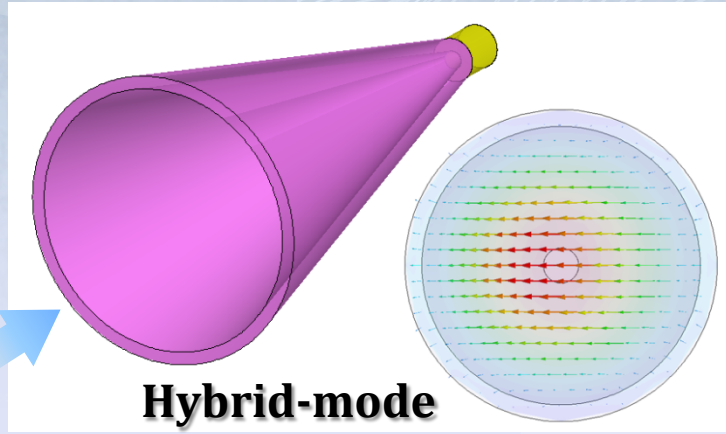
E. Lier and R. K. Shaw, *Electron. Lett.*, vol. 44, pp. 1444-1445, 2008.
E. Lier, *IEEE Antennas and Propag. Magazine*, vol. 52, no. 2, pp. 31-39, 2010.

Broadband Hybrid-mode Horn with Metamaterial Liner

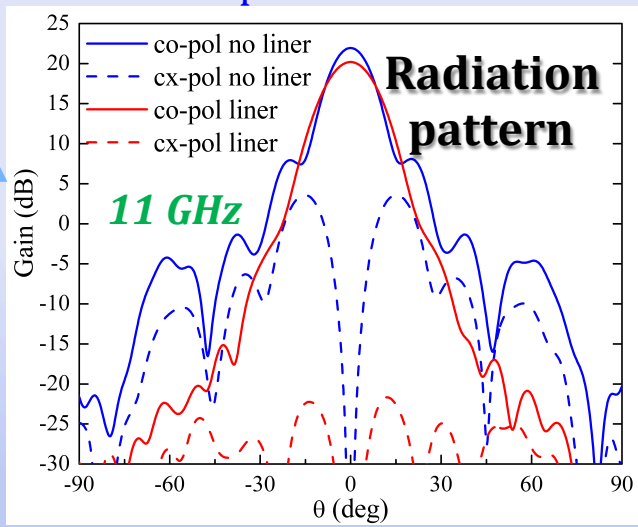


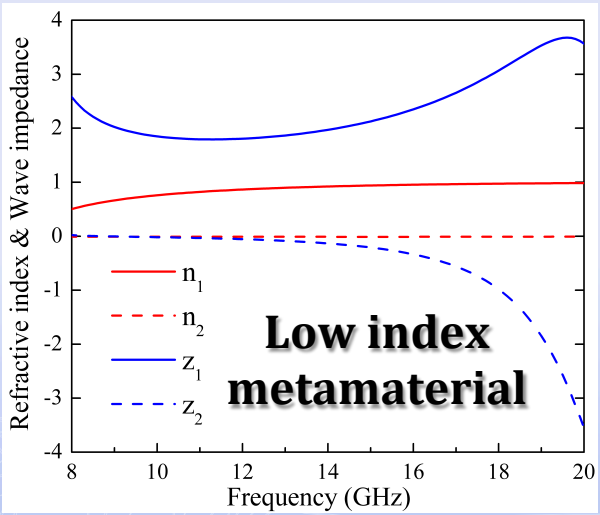
Metasurfaces optimized to support balanced-hybrid mode





Hybrid-mode horn with low sidelobes and low cross-polarized radiation



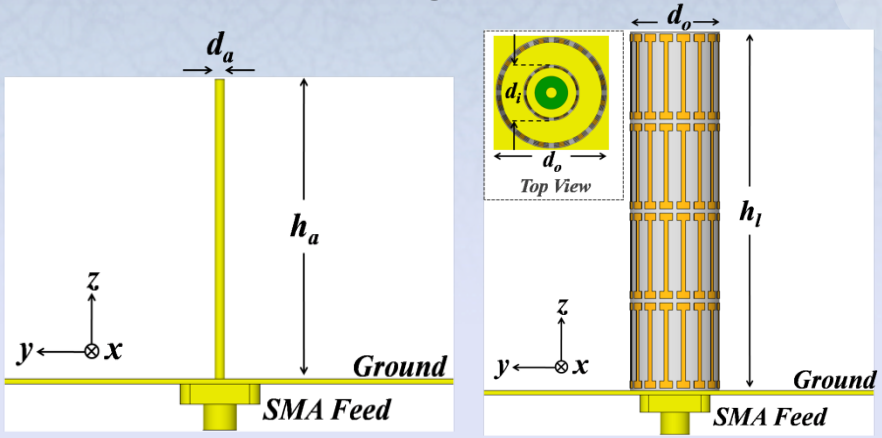


Effective material parameters by specialized inversion algorithms

Q. Wu, C. P. Scarborough, D. H. Werner, E. Lier, and X. Wang, "Design Synthesis of Metasurfaces for Broadband Hybrid-mode Horn Antennas with Enhanced Radiation Pattern and Polarization Characteristics," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 8, pp. 3594-3604, Aug. 2012.

Anisotropic Metamaterial Coating – Configuration and Design

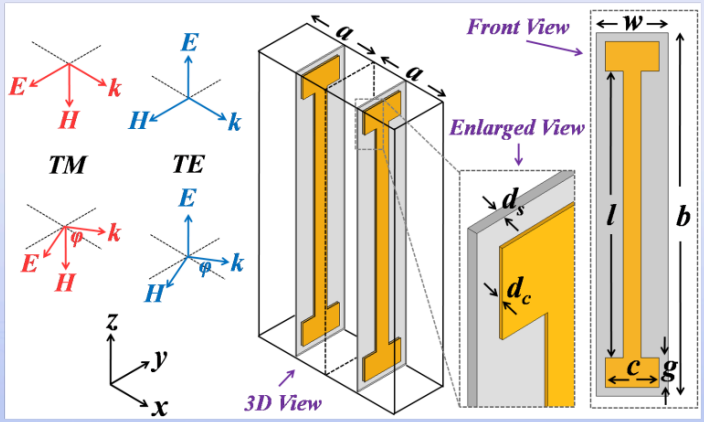
Configuration



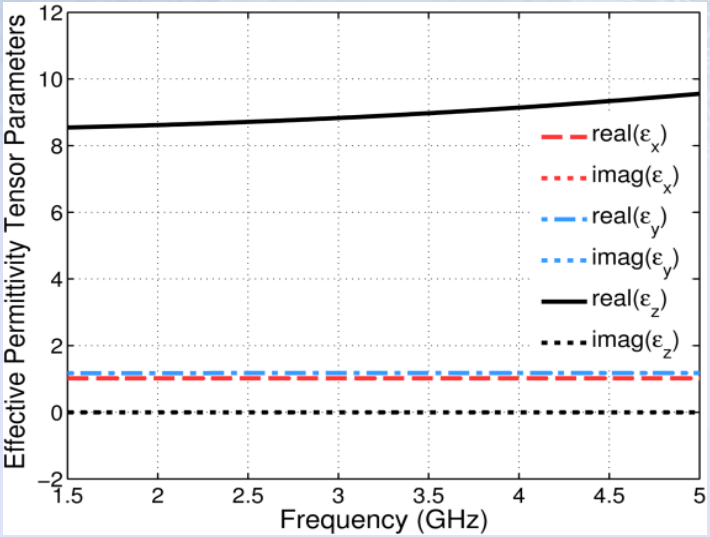
Monopole

With MM Coating

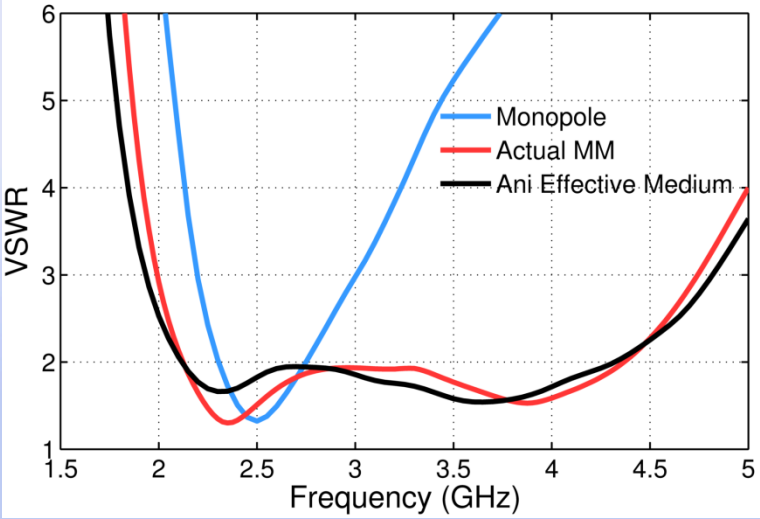
Unit Cell Geometry and Dimensions



Effective Medium Properties



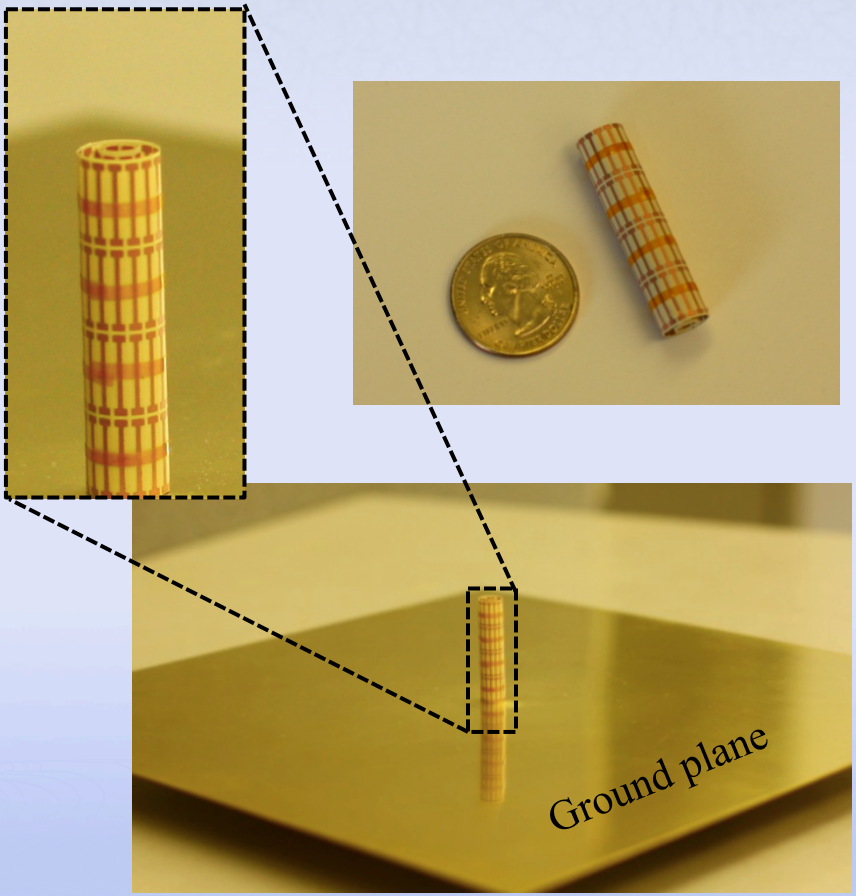
Integrated Simulation

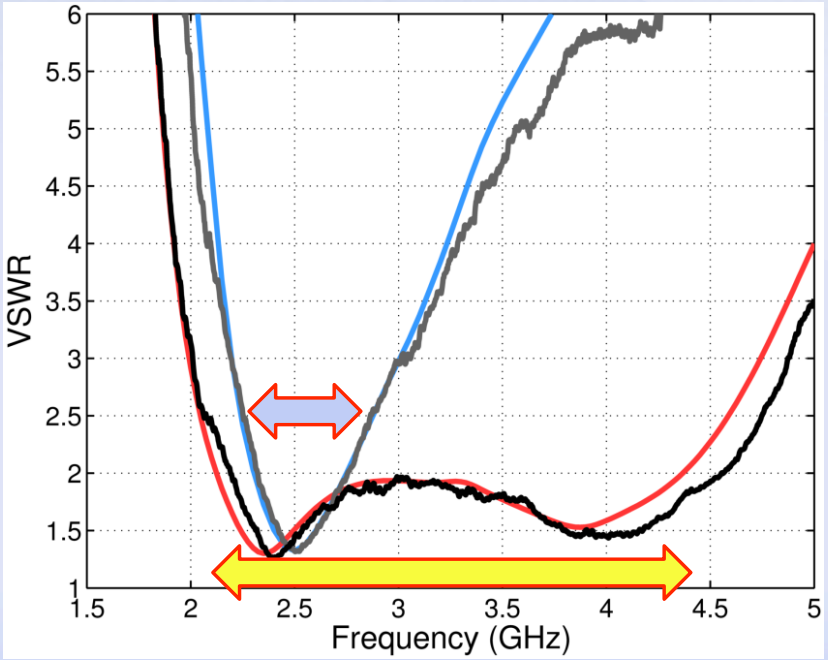


Z. H. Jiang, M. D. Gregory and D. H. Werner, *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1543-1546 (2011).

Anisotropic Metamaterial Coating – Fabrication and Measurement

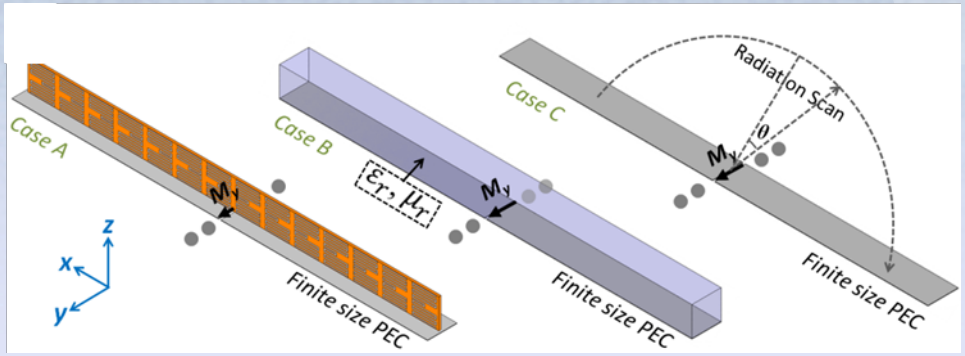
- Enhances the bandwidth of a conventional monopole to over an octave.
- The anisotropic metamaterial coating is compact, lightweight and low-cost.



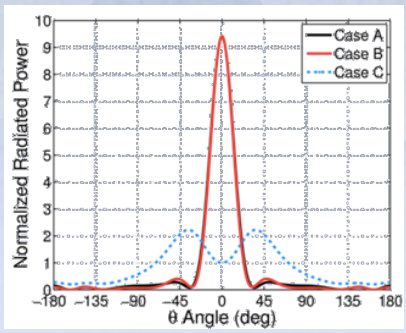


Blue line: Simulated monopole alone.
Gray line: Measured monopole alone.
Red line: Simulated monopole with MM.
Black line: Measured monopole with MM.

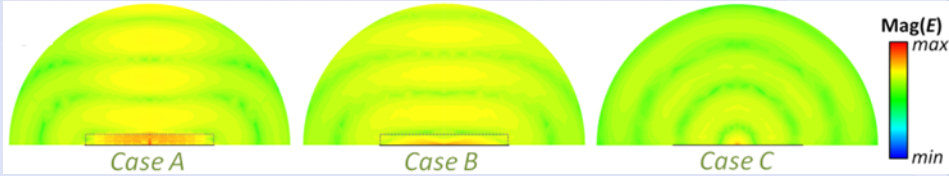
Enhanced Electromagnetic Radiation Using Subwavelength Profile Leaky Metamaterial Coating



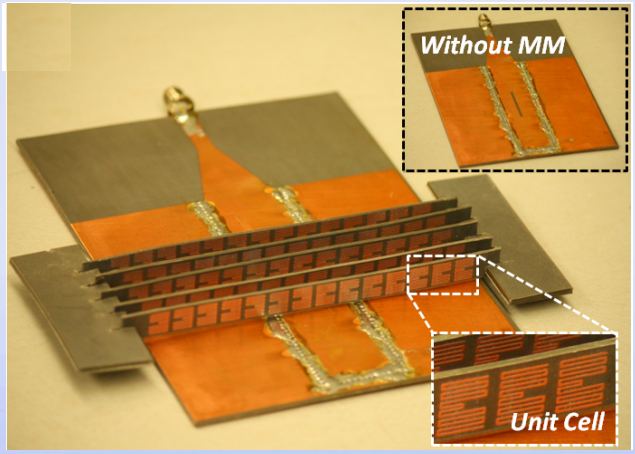
Full wave simulations of infinite array along the *y*-direction

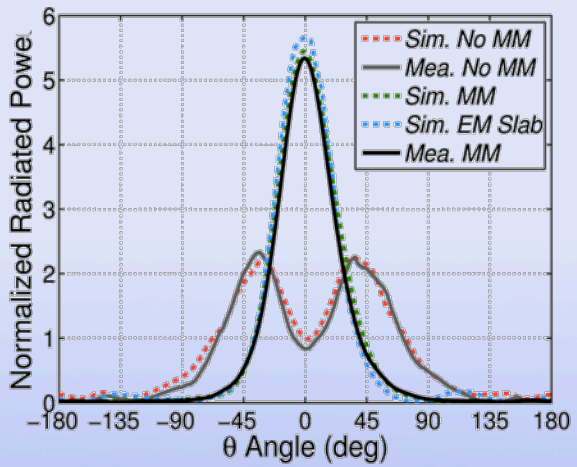


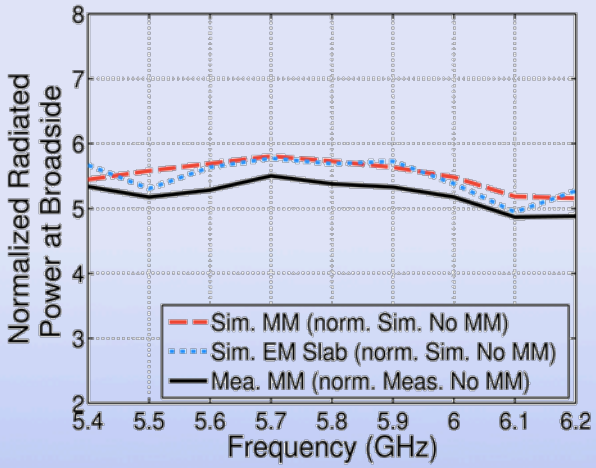
Normalized radiated power for the three cases at 5.4 GHz (*i.e.* close to the effective plasma frequency of the metamaterial)



Near- and far-zone electric field distribution





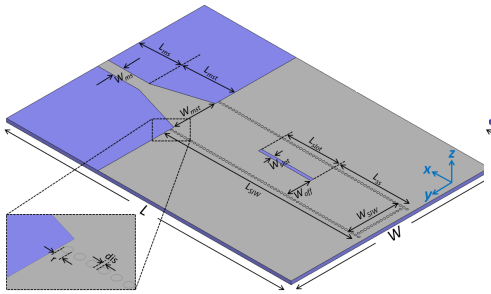


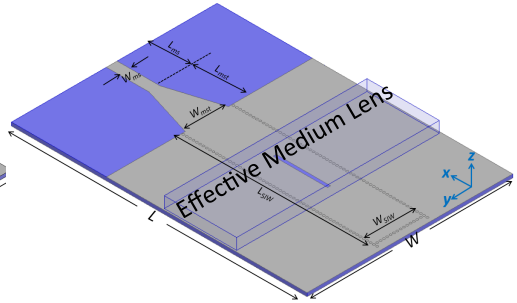
Using a substrate integrated waveguide fed slot antenna as a quasi-TM source, we experimentally demonstrated a 0.12λ metamaterial coating providing unidirectional radiation with over 5-fold radiation power enhancement over a wide band.

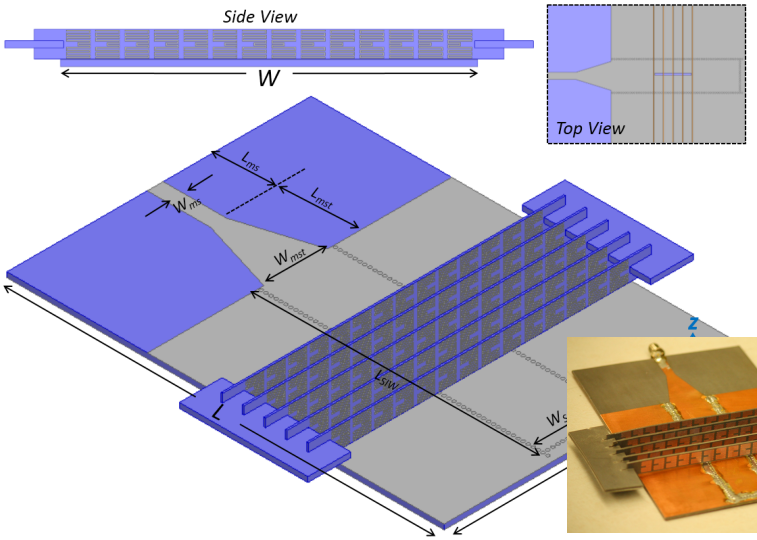
Z. H. Jiang, Q. Wu, and D. H. Werner, Phys. Rev. B, **86**, 125131/1-7 (2012).

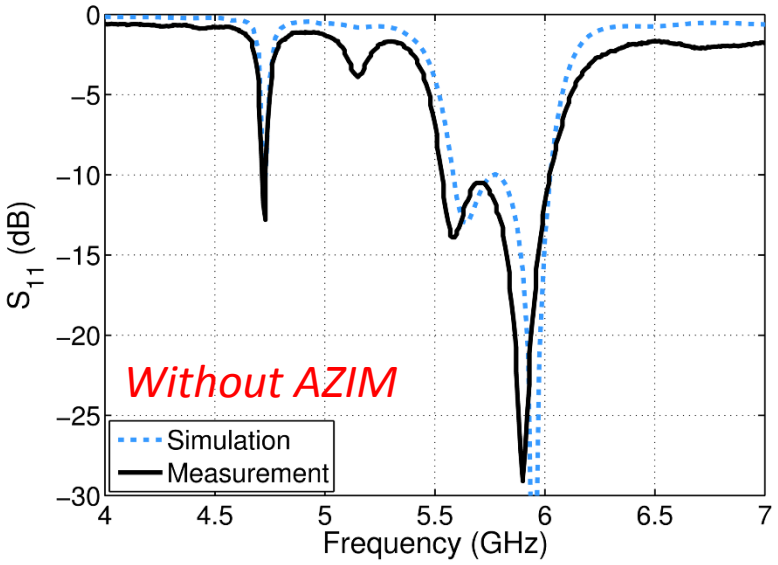
Integrated Antenna Performance

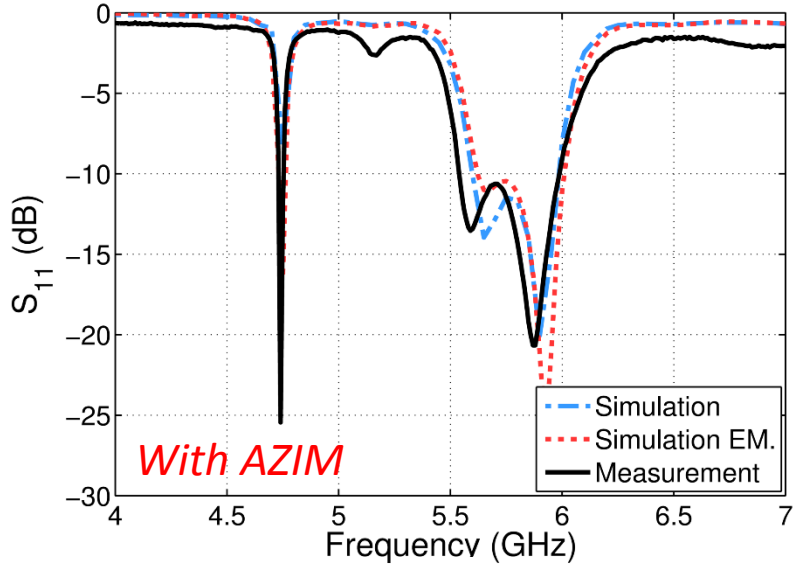
Impedance of slot w/wo AZIM coating.







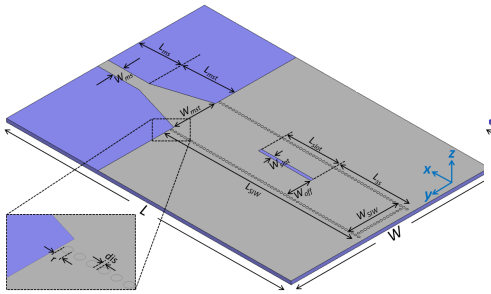


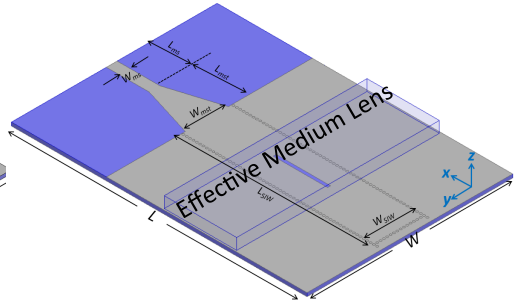


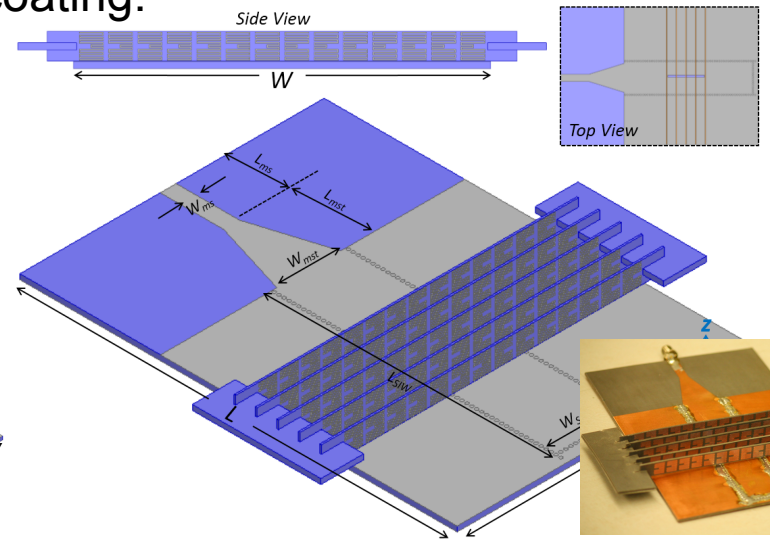
- The added AZIM coating does not significantly affect the impedance of the SIW fed slot antenna.
- Simulation using effective medium lens agrees well with that using actual discrete

Integrated Antenna Performance

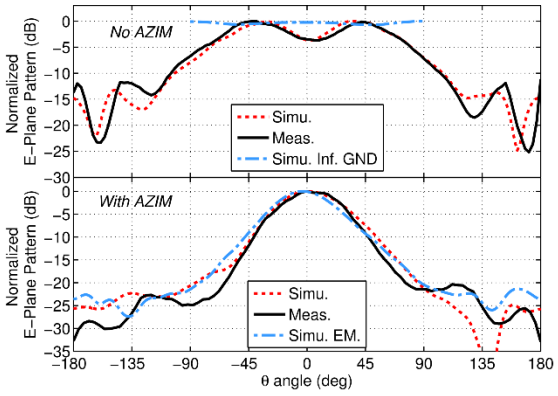
E-plane radiation patterns of slot w/wo AZIM coating.



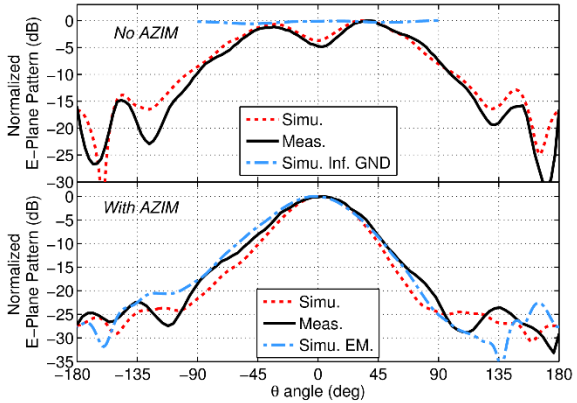




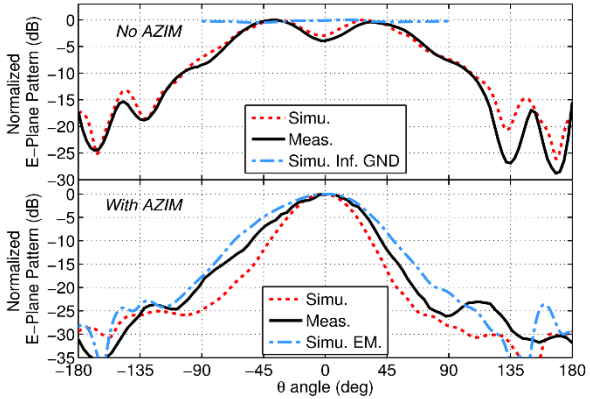
E-plane normalized radiation patterns



5.6 GHz



5.8 GHz



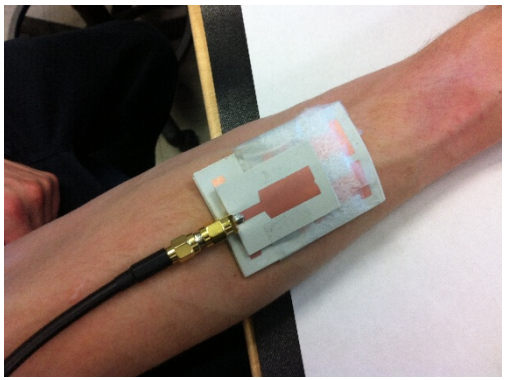
6.0 GHz

- The double-peak radiation patterns caused by finite ground plane diffraction are eliminated.
- A stable sharp peak pointing at broadside is achieved with AZIM coating (total thickness: 0.12λ).

Metasurface-enabled Wearable Antenna

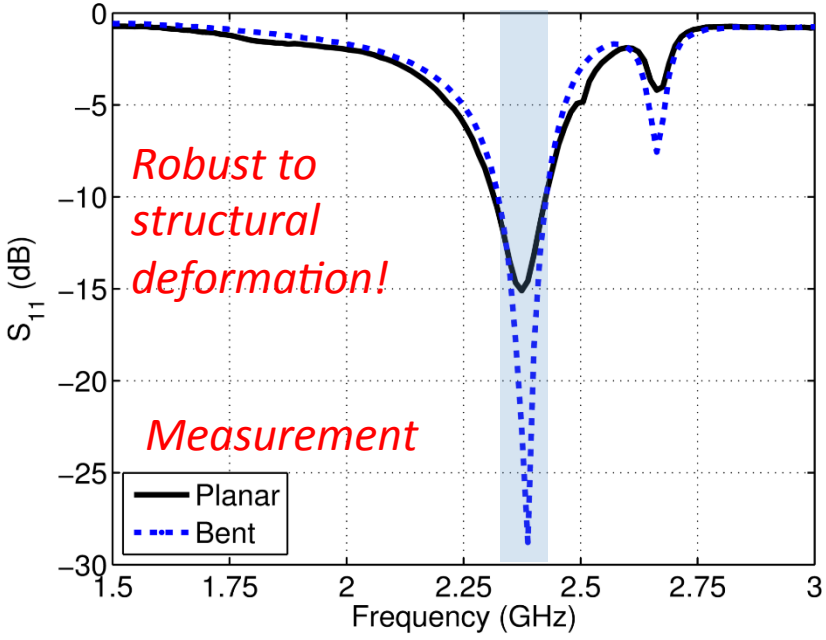
--- 2.4 GHz MBAN band antenna measurements

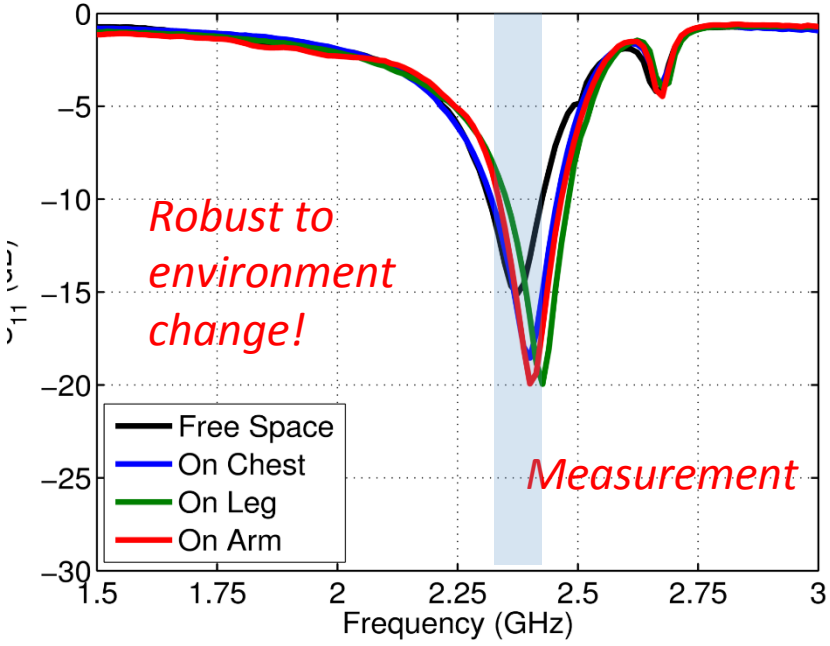
Integrated Antenna Being Bent



Integrated Antenna Conformed to Body

Reflection at Input Port of the Antenna

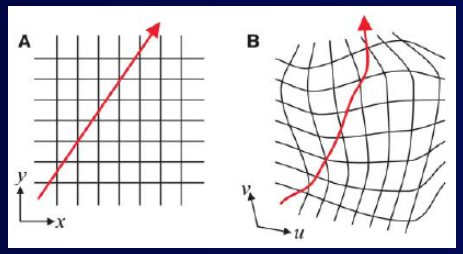


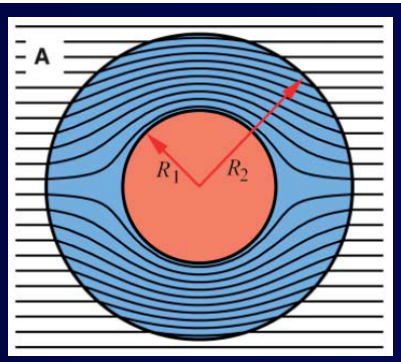


Z. H. Jiang, D. E. Brocker, P. E. Sieber, and D. H Werner, "A Compact, Low-Profile Metasurface-Enabled Antenna for Wearable Medical Body-Area Network Devices," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 8, pp. 4021-4030, Aug. 2014.

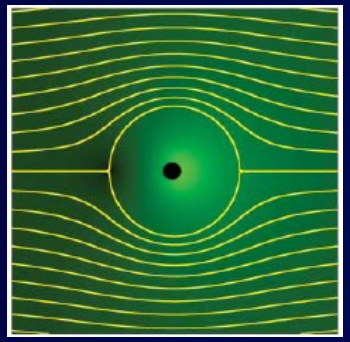
Transformation Approach

Coordinate Transform



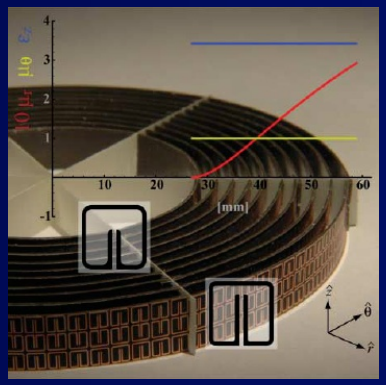


Pendry *et al.*, *Science* **312,** 1780 (2006)

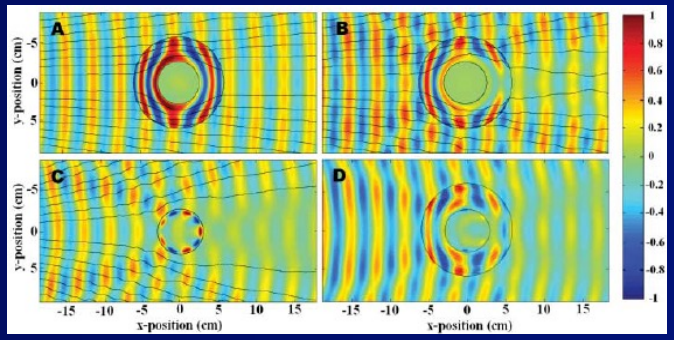


Leonhardt, *Science* **312,** 1777 (2006)

Experiment

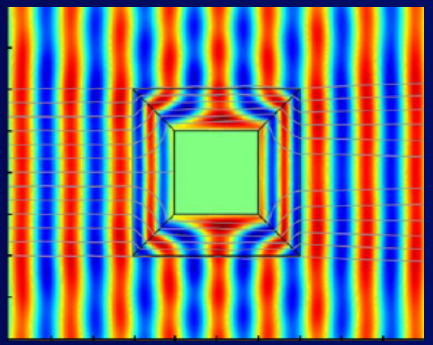


Microwave Regime

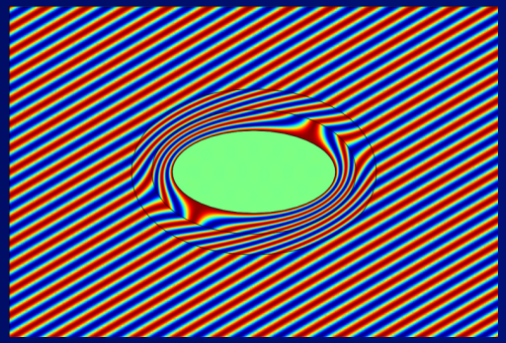


Schurig *et al.*, *Science,* **314,** 977 (2006)

Other Cloak Geometries (Simulations)

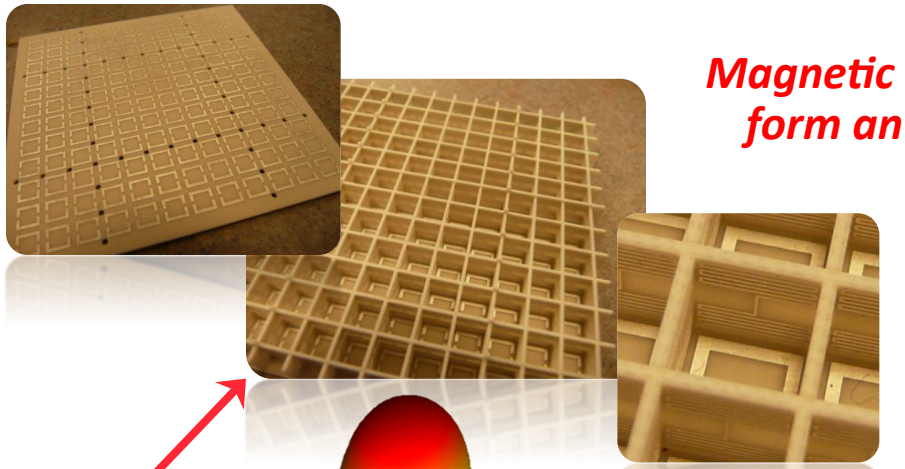


Rahm *et al.,* Photon. Nanostruct. **6,** 87-95 (2008)



Kwon and Werner, APL **92,** 113502 (2008)

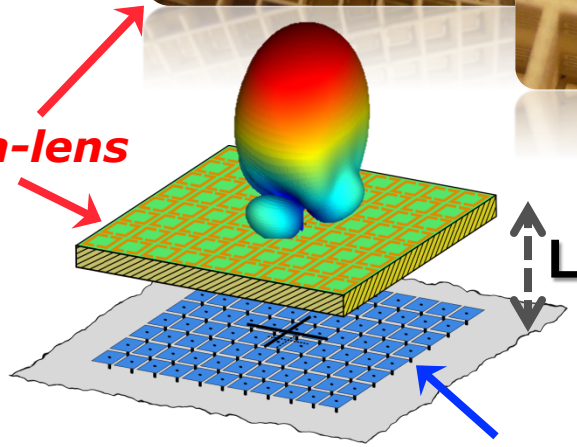
A Compact Directive Antenna Combining Collimating Meta-lens and AMC Ground Plane



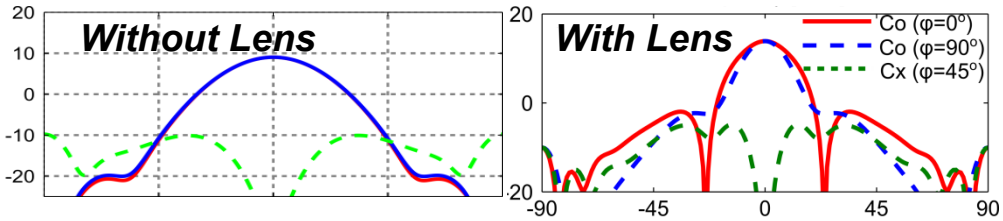
Magnetic and electric molecules are combined to form an anisotropic low-index metamaterial.

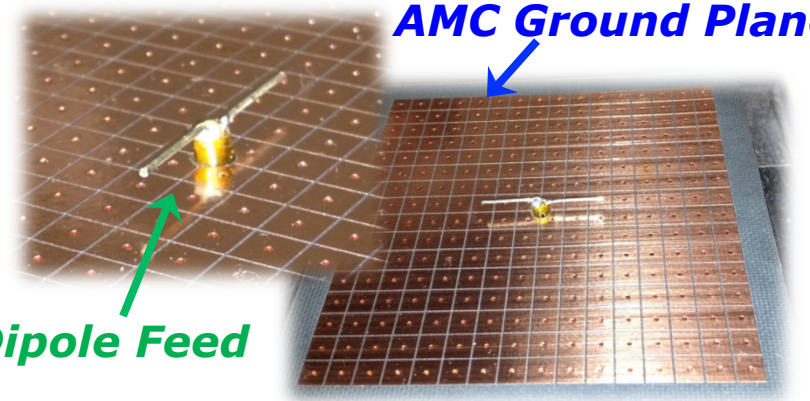
Transformation electromagnetics inspired dual-polarization collimating meta-lens

- Dual-metamaterial antenna design
- Printed circuit board construction compact, lightweight, and low cost
- Simple feed, high gain antennas for space applications



6 dB gain improvement with 10% bandwidth





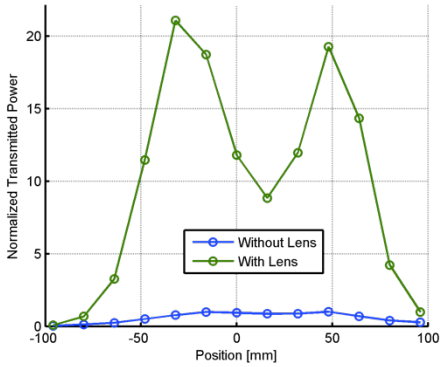
An artificial magnetic conducting (AMC) ground plane reduces the antenna profile by over 20% while maintaining good radiation efficiency.

J. Turpin, Q. Wu, D. H. Werner, B. Martin, M. Bray and E. Lier, "Near-Zero-Index Metamaterial Lens Combined with AMC Metasurface for High-Directivity Low-Profile Antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 4, pp. 1928-1936, April 2014.

Super-Resolution / TO Lenses

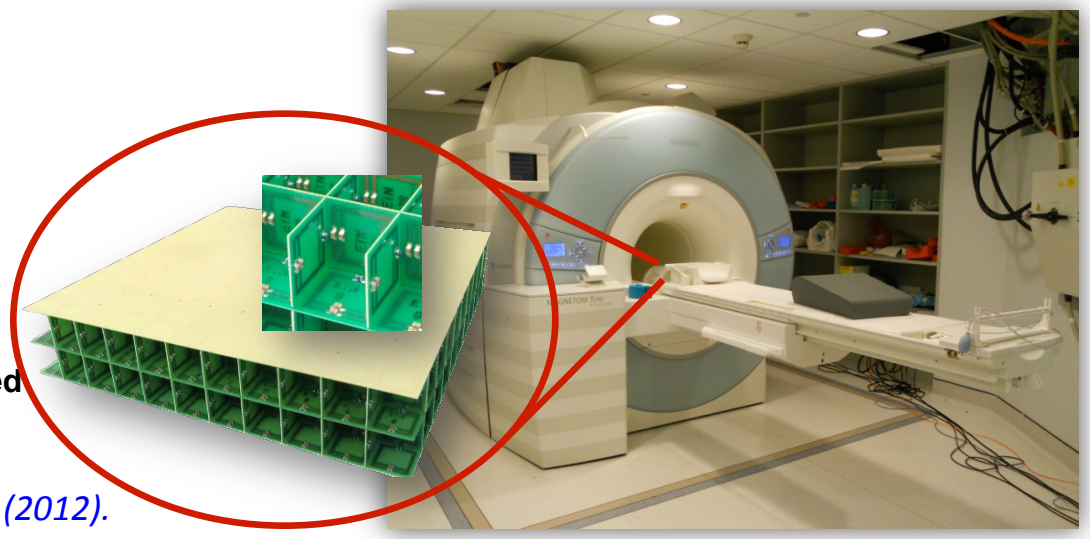
Isotropic μ = -1 Metamaterial for MRI Enhancement at 8.5MHz for Prostate Cancer Detection

Low-frequency performance is made possible by ring resonators loaded with capacitors and inductors.



With the lens (green), the lens resolves two magnetic sources that cannot be distinguished without the lens (blue).

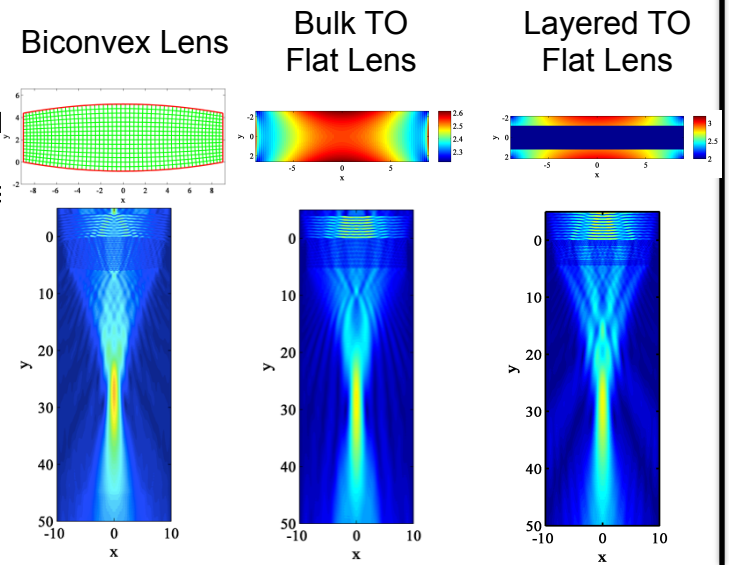
The lens also increases the received magnetic field by a factor of 20 or more.



C. Scarborough, et al., Appl. Phys. Lett., 101, 014101 (2012).

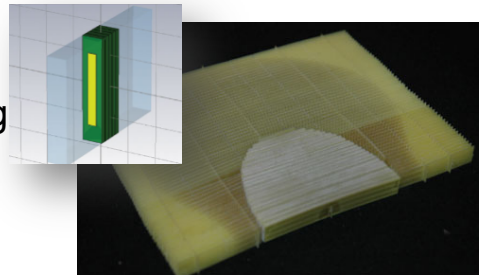
Transformation Optics Gradient Index Flat Lens

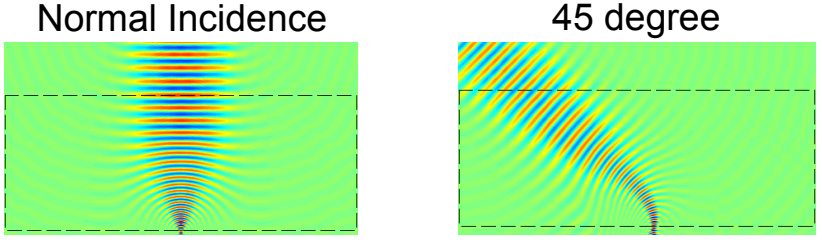
Many TO designs require impractical material properties, but this uses a quasi-conformal mapping to create a design with broadband, low-loss, gradient-index materials.



Extreme-Angle Broadband Metamaterial Flat Lens by Transformation Optics

The lens works by an index of refraction tapering from 1 at the edges to 4 in the focal plane.



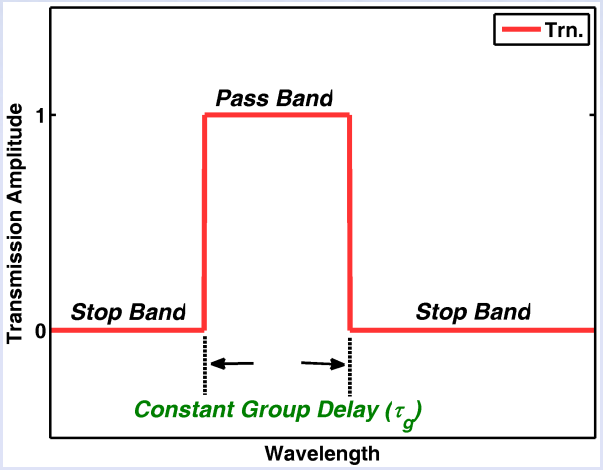


PENNSTATE

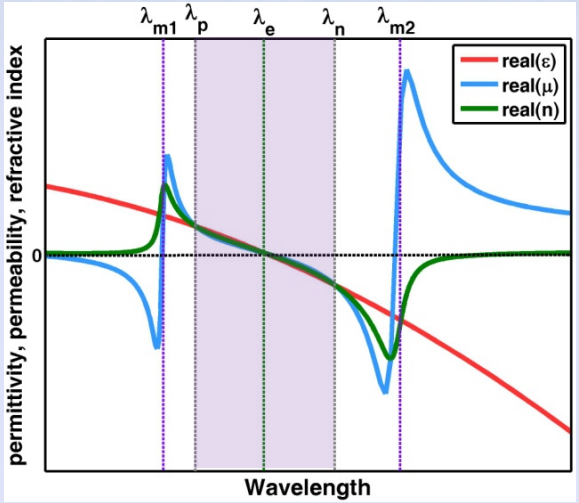
Broadband Dispersion Engineered Photonic Metamaterial

- Design approach involves tailoring both effective permittivity and permeability profiles of the metamaterial.
- Metamaterial filter achieves a broadband flat-top transmission band and suppressed group delay variation.
- Metamaterial prism achieves wavelength-dependent beam steering (along with filter functionality).

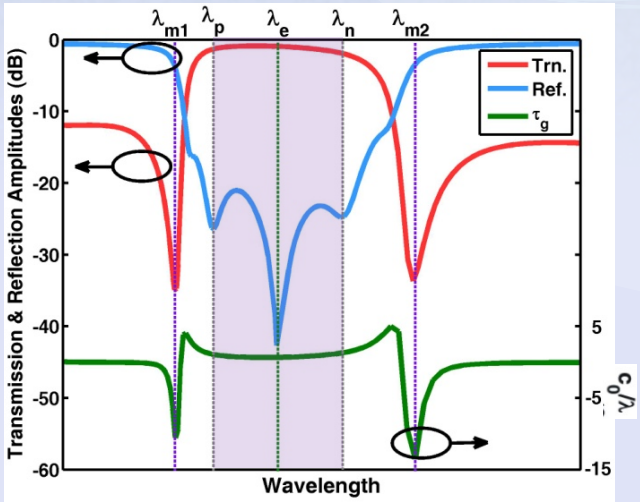
Proposed Dispersive Negative-Zero-Positive Index Metamaterial (Applications: Broadband Filter and Beam Steering Prism)



Idea Filter Response



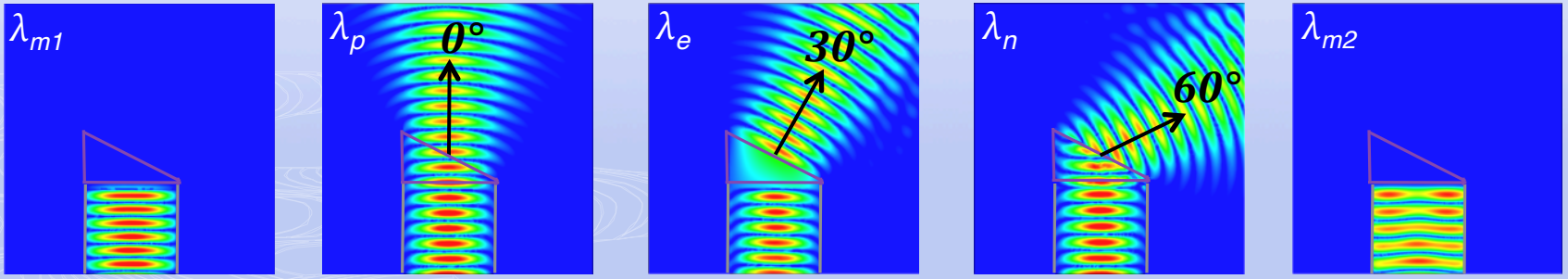
Required Effective Medium Properties



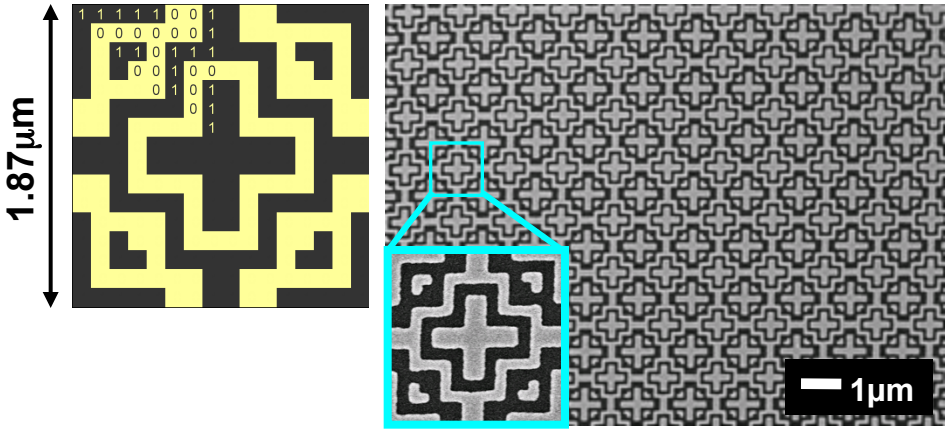
Effective Medium Slab Performance

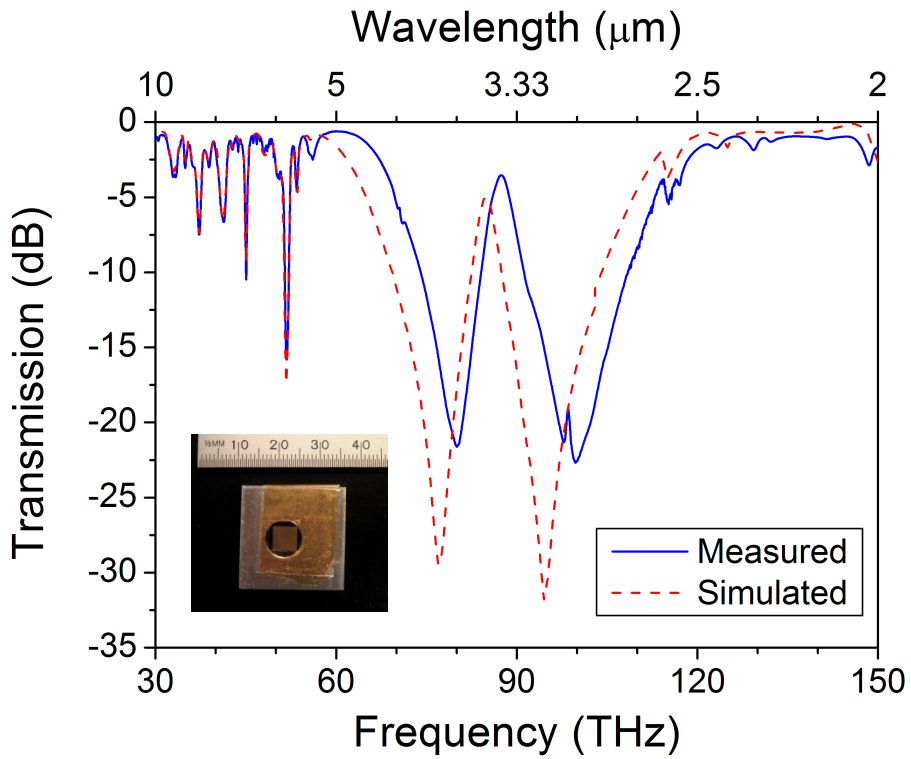
(Prism)

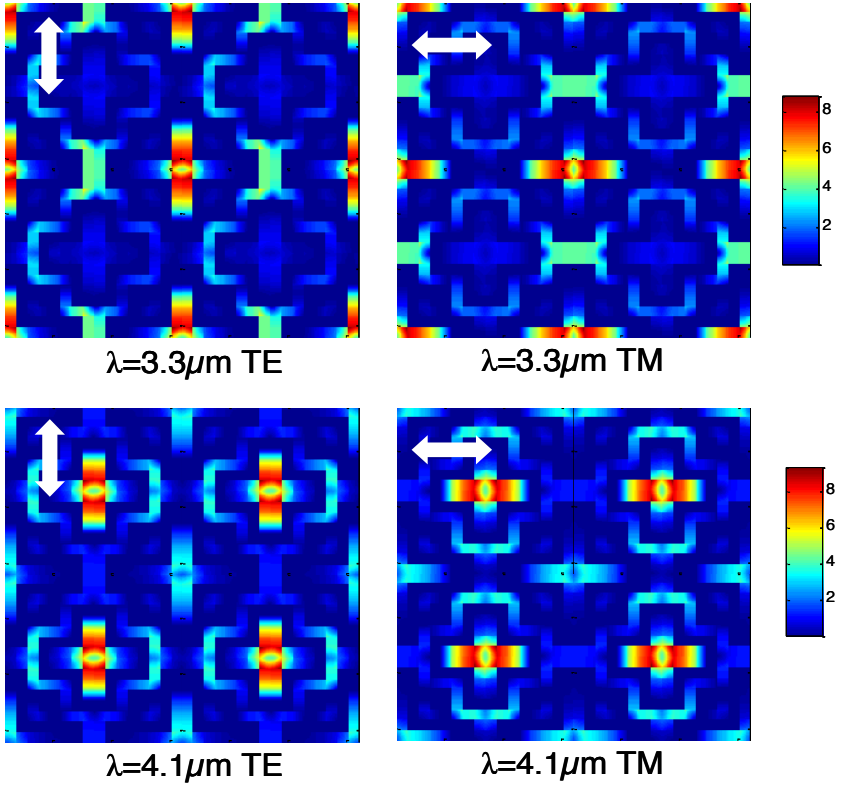
Performance of a prism with a 30 tilt angle composed of the effective medium shown above.



Metallodielectric mid-infrared filter





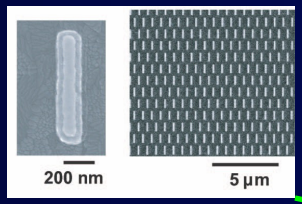


Excellent (>20 dB attenuation) multiband filter performance superior to state-of-the-art conventional designs in the IR

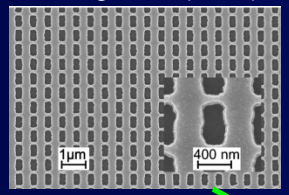
Y. Tang, J. A. Bossard, D. H. Werner, and T. S. Mayer, "Single-Layer Metallodielectric Nanostructures as Dual-band Midinfrared Filters," *Applied Physics Letters*, 92, 263106, 2008.

Optical Metamaterials

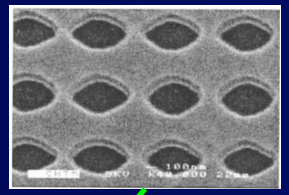
Shalaev et al. (2005)



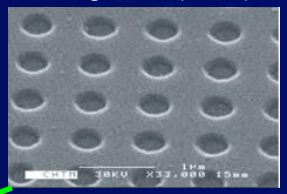
Dolling et al. (2006)



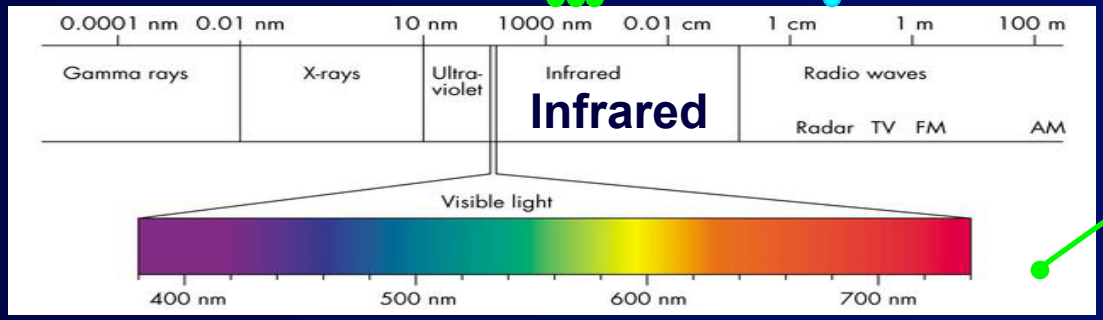
Zhang et al. (2006)



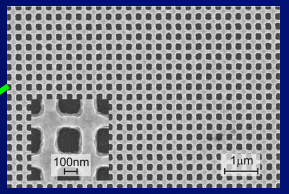
Zhang et al. (2005)



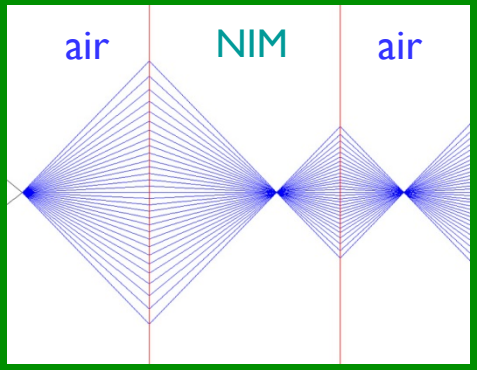
Shelby et al. (2001)



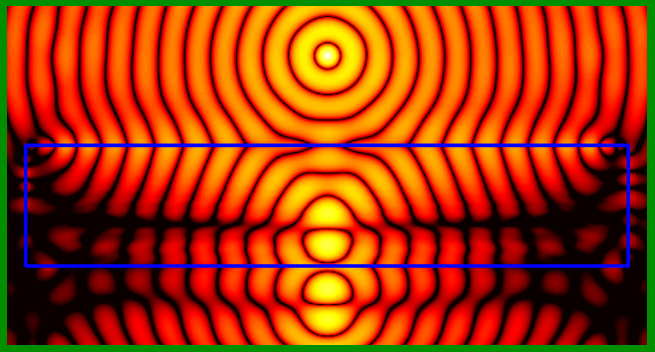
Dolling et al. (2007)



Potential applications



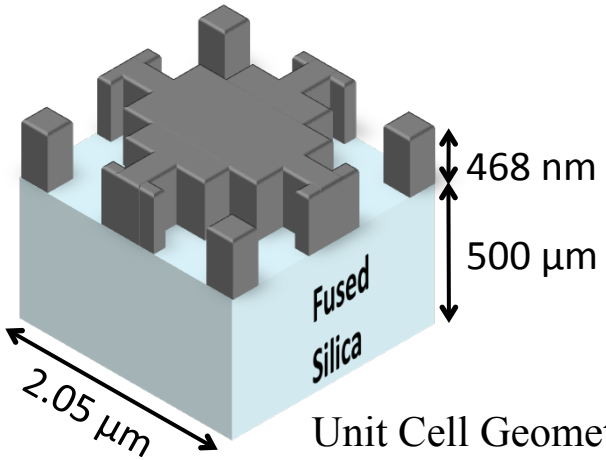
- Flat optical lens
- Sub-wavelength imaging



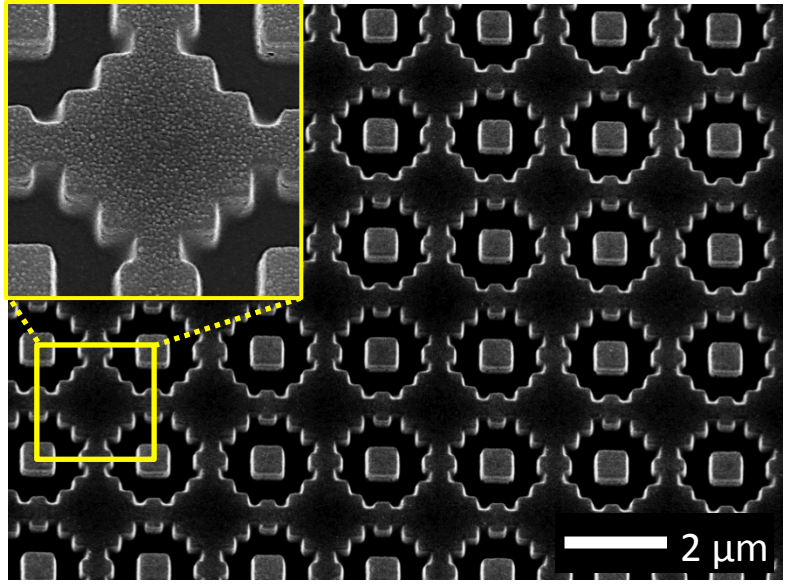
2.3λ×11.54λ slab at 3.46THz

All Dielectric Zero Index Metamaterial Mirror

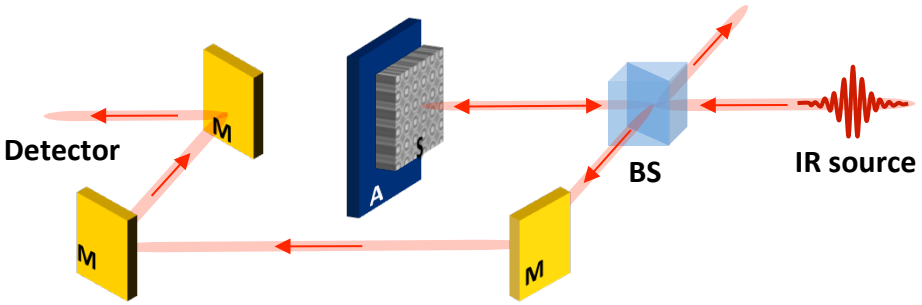
- Artificial mirror created from all dielectric guided wave structure – lower loss than metallic structure.
  - A perfect mirror can be achieved with a metamaterial slab having: Re(n)→0, Im(n)→-∞, Re(z)→0
  - Realized by pixelized aSi structure optimized using genetic algorithm.



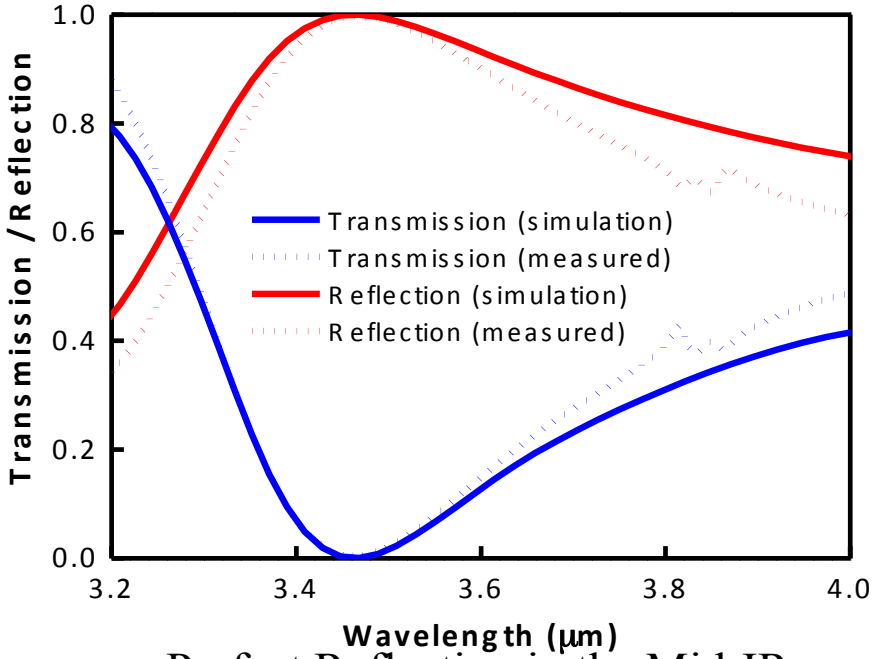
Unit Cell Geometry



S. Yun, et al., Appl. Phys. Lett., 102, 171114 (2013).



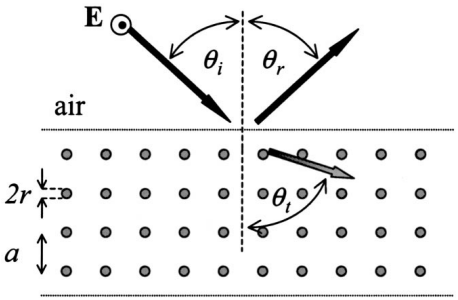
Normal Incidence Reflection Measurement Setup



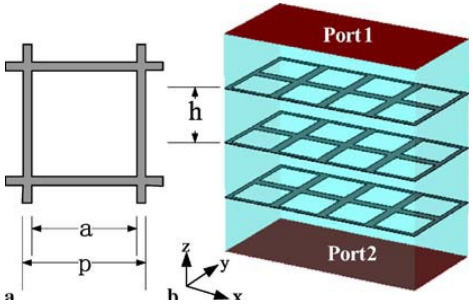
Perfect Reflection in the Mid-IR

Previous Examples of ZIM Designs

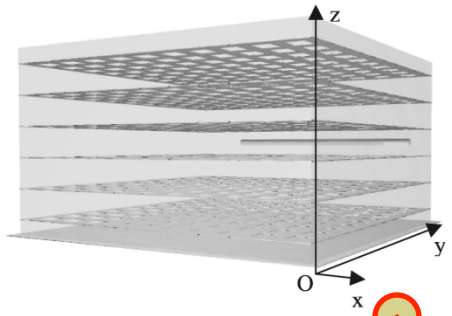
*Schwartz and Piestun, JOSA B **20**, 2448–2453 (2003).



*Wu *et al.*, Appl. Phys. A **87**, 151–156 (2007).



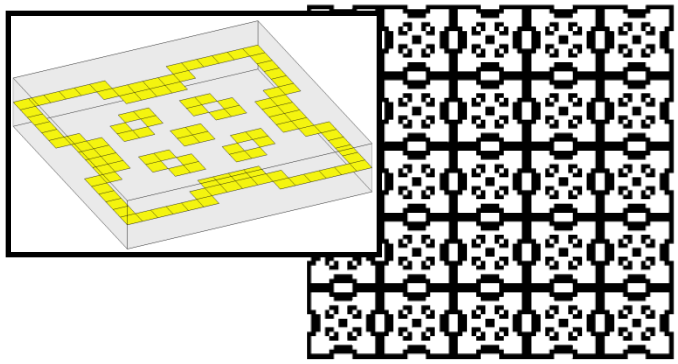
*Enoch *et al.*, PRL **89**, 213902 (2002).



All ε→0 metamaterials

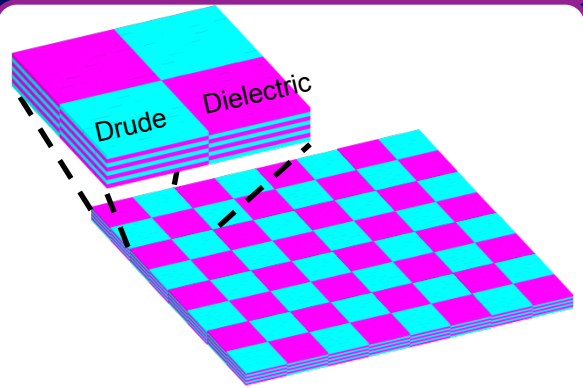
Wire or wire mesh

Optimized FSS Screen



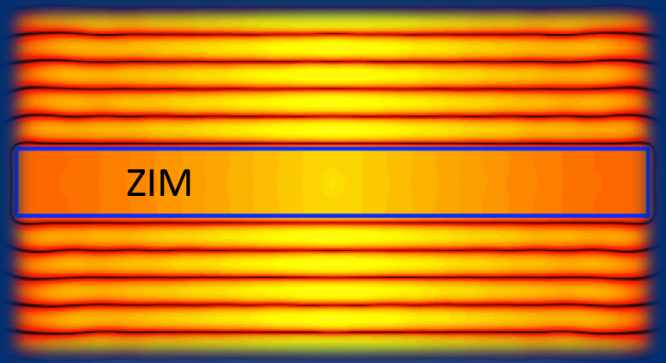
*Gingrich and Werner, Elec. Lett. **41**, 1266-1267 (2005).

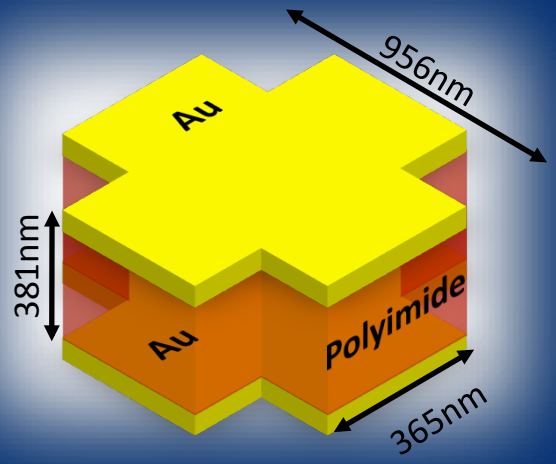
Stacked Drude Material



*Kwon *et al.*, Elec. Lett. **43**, 319-320 (2007).

Optical Zero-Index Metamaterial





Optimized parameters at 1550 nm

n_{eff} = 0.069-0.054j ≈ 0

Z_{eff}/Z_0 = 1.01-0.023j ≈ 1

|T| = 0.919= -0.73dB

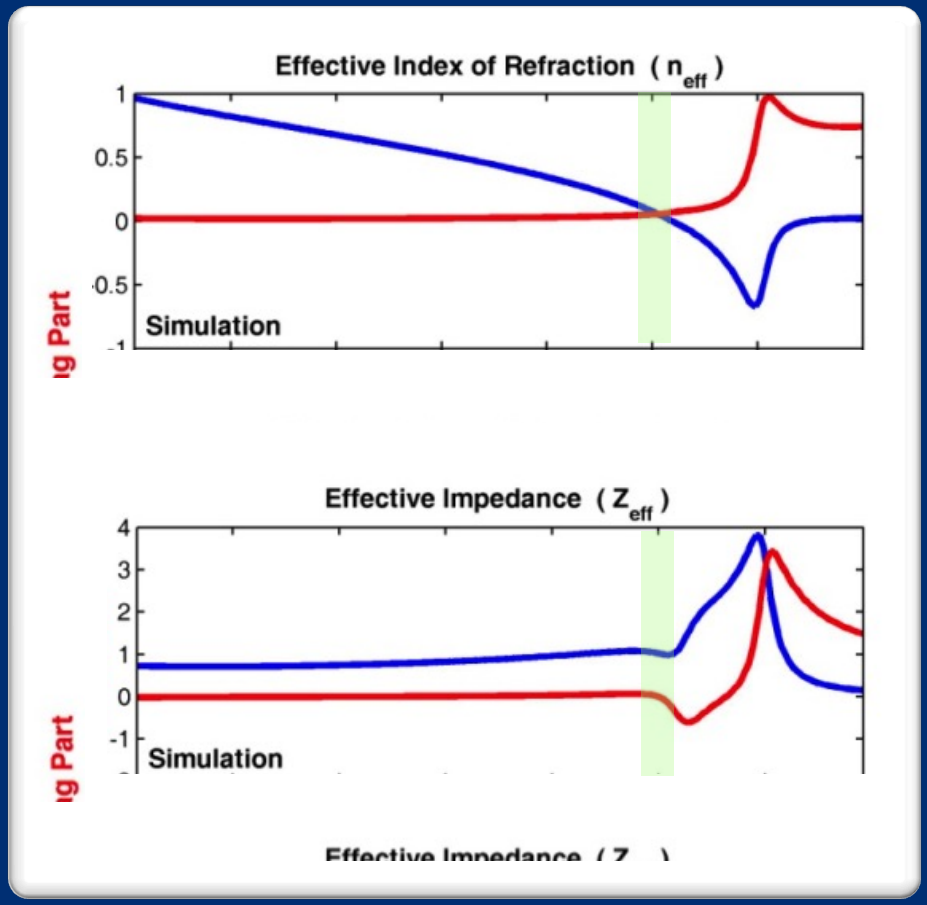
|R| = 0.0033= -49.64dB

|A| = 0.1552= -8.09dB

Zero Index Metamaterials

-Less studied compared to negative indices

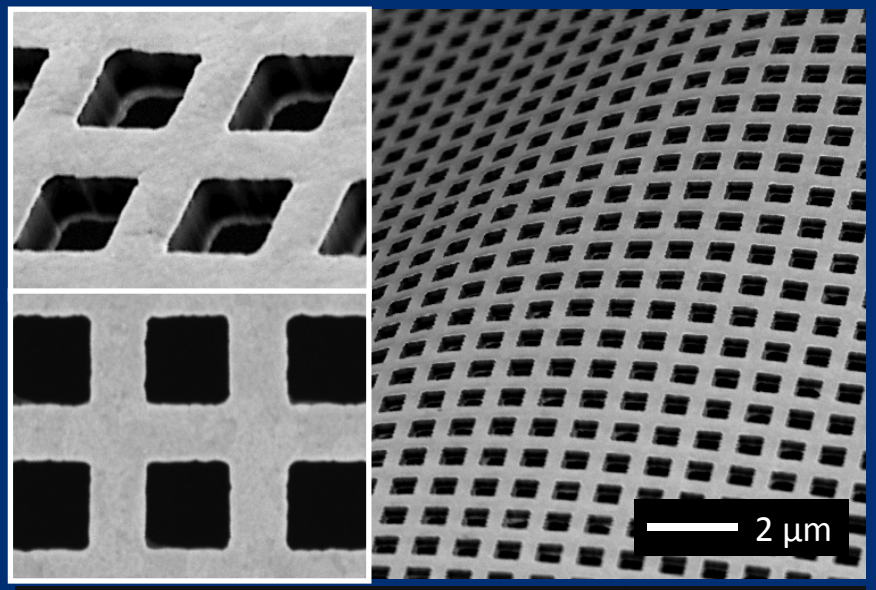
-Phase delay lines, collimators, angle filters, etc

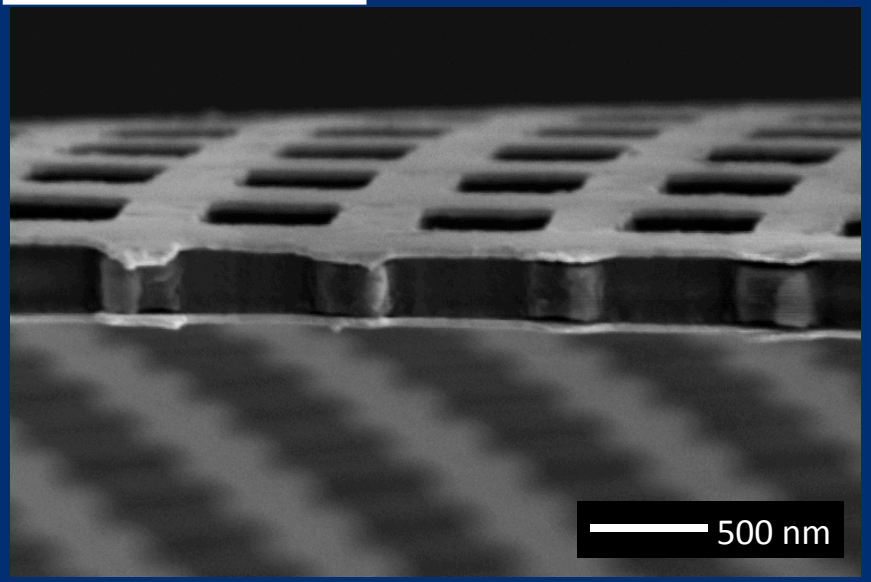


Impedance matched zero index achieved

*S. Yun, Z. H. Jiang, Q. Xu, Z. Liu, D. H. Werner, & T. S. Mayer, *ACS Nano* **6**, 4475-4482 (2012)

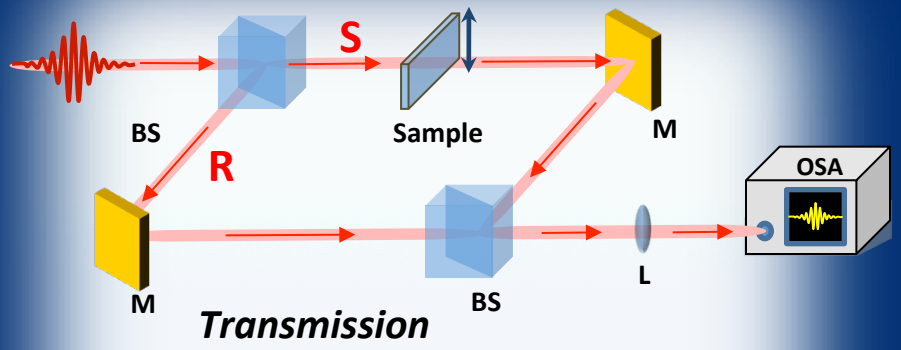
Fabrication & Measurement of ZIM

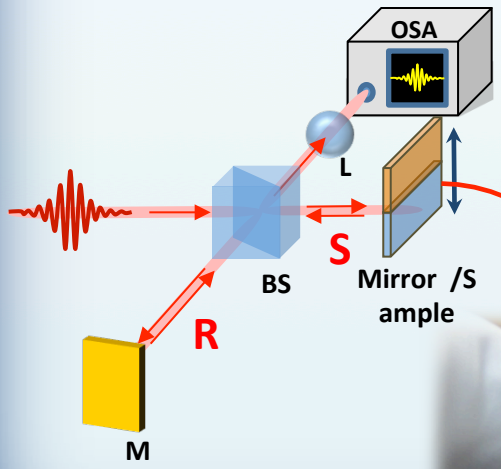


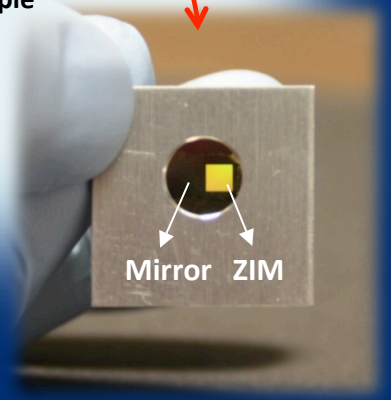


Free standing structure with vertical sidewalls

Spectral Holography



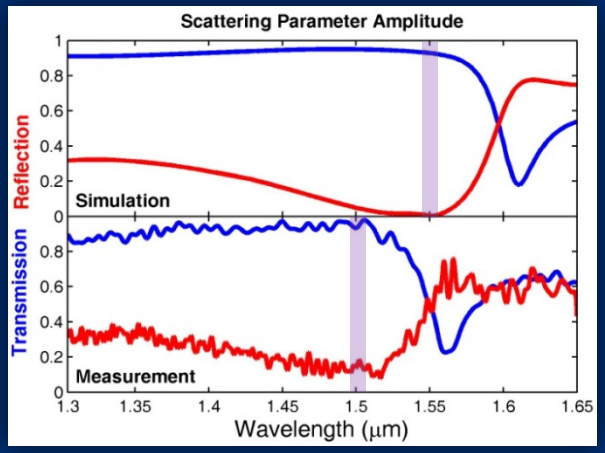


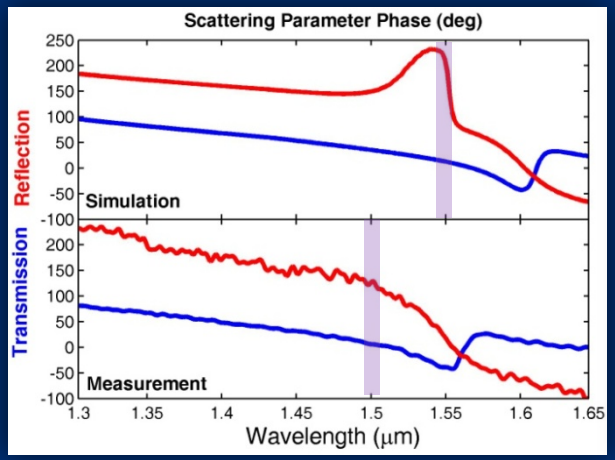


*S. Yun, Z. H. Jiang, Q. Xu, Z. Liu, D. H. Werner, & T. S. Mayer, *ACS Nano* **6**, 4475-4482 (2012)

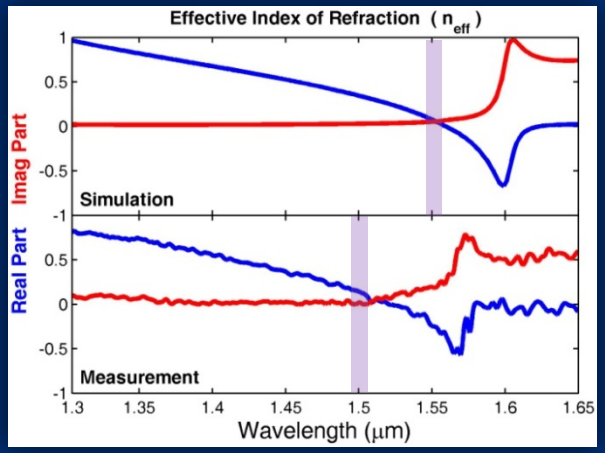
Simulated and Measured Results

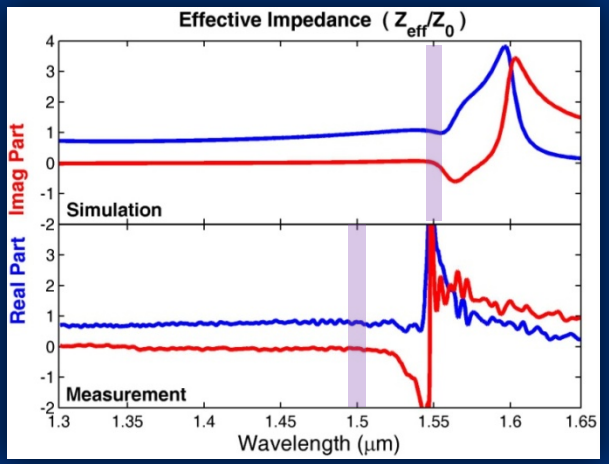
Scattering Parameters



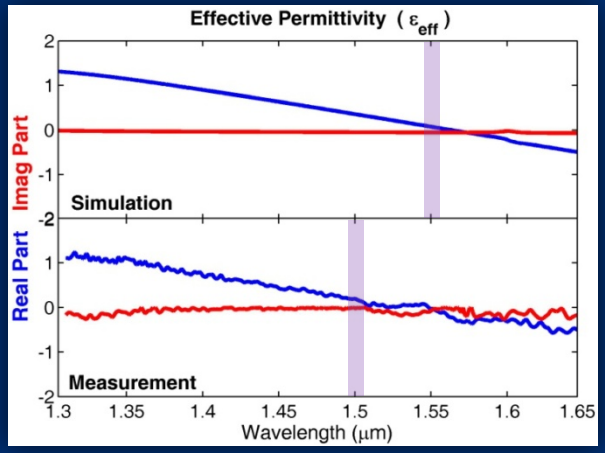


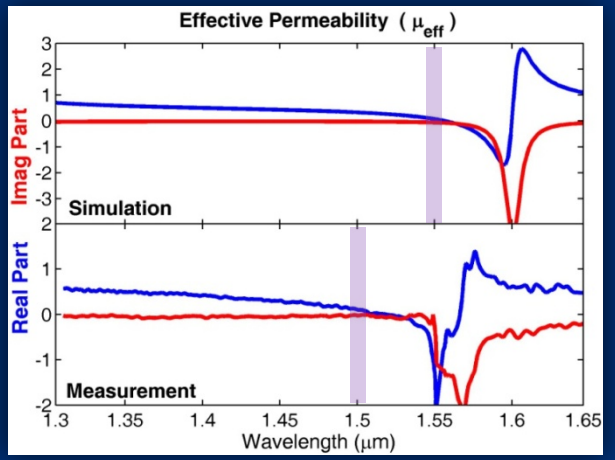
n_{eff} & Z_{eff}





ε_{eff} & μ_{eff}





Simulated (1.55μm): n_{eff}=0.07+0.05i Z_{eff}=1.01-0.02i |T|~95%

Measured(1.50μm): n_{eff}=0.12+0.03i Z_{eff}=0.86-0.05i |T|~95%

*S. Yun, Z. H. Jiang, Q. Xu, Z. Liu, D. H. Werner, & T. S. Mayer, *ACS Nano* **6**, 4475-4482 (2012)

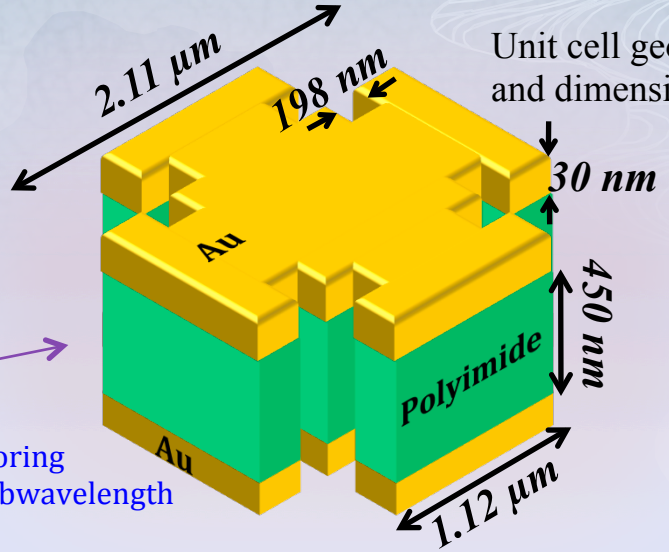
BDE Enabled Photonic Metamaterial Filter

Design goals

-Wavelength range of interest: 2.5-4 μm

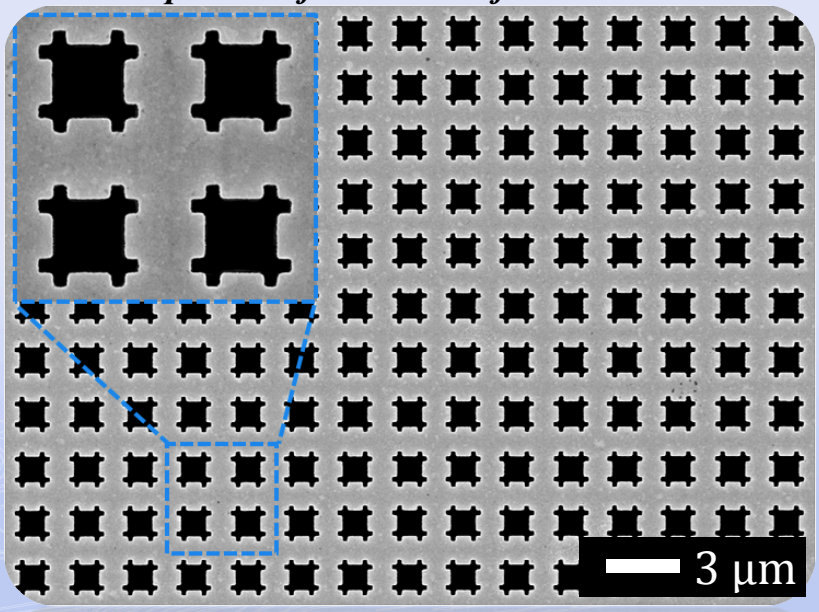
- Flat top filter function 3-3.5 μm
- Suppressed group delay variation

Optimized Metamaterial Filter Structure

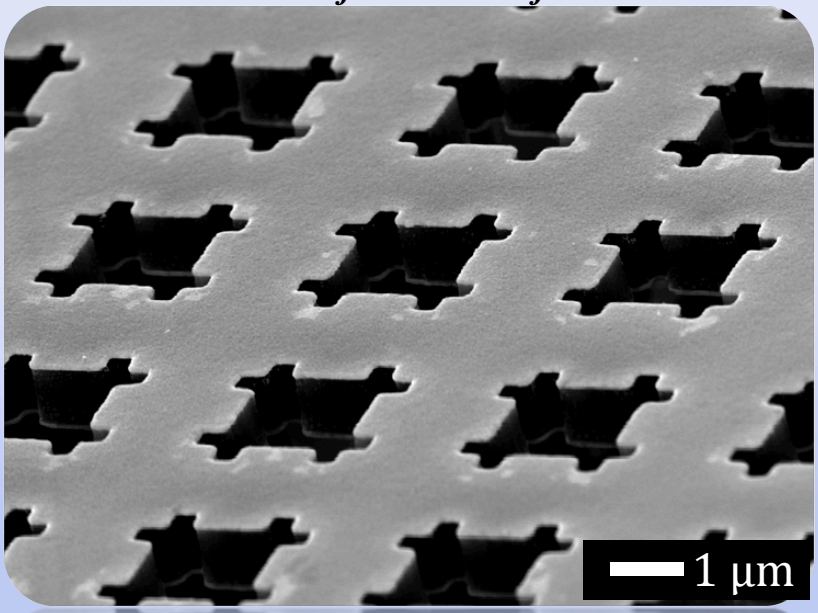


Z. H. Jiang, S. Yun, L. Lin, J. A. Bossard, D. H. Werner, and T. S. Mayer, "Tailoring Dispersion for Broadband Low-loss Optical Metamaterials Using Deep-subwavelength Inclusions," *Scientific Reports*, Vol. 3, pp. 1571/1-9, March 2013.

Top-View of a Portion of the Filter

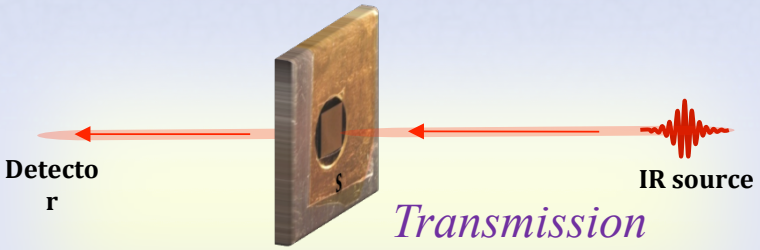


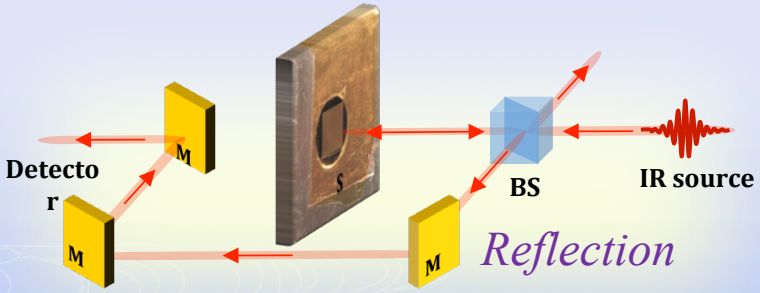
Tilted View of a Portion of the Filter

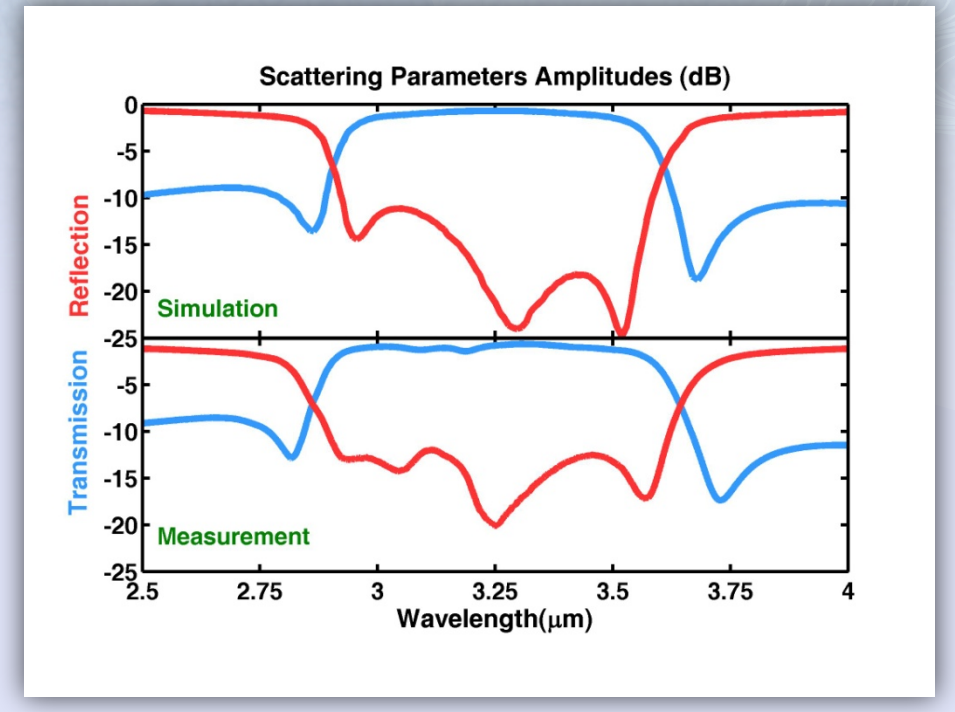


FTIR Measurements

Optical Setup for Characterization







Transmission band: 2.95-3.50 μm (~ -1 dB)
Transmission variation: < 0.6 dB
Outside the band: < -8.3 dB